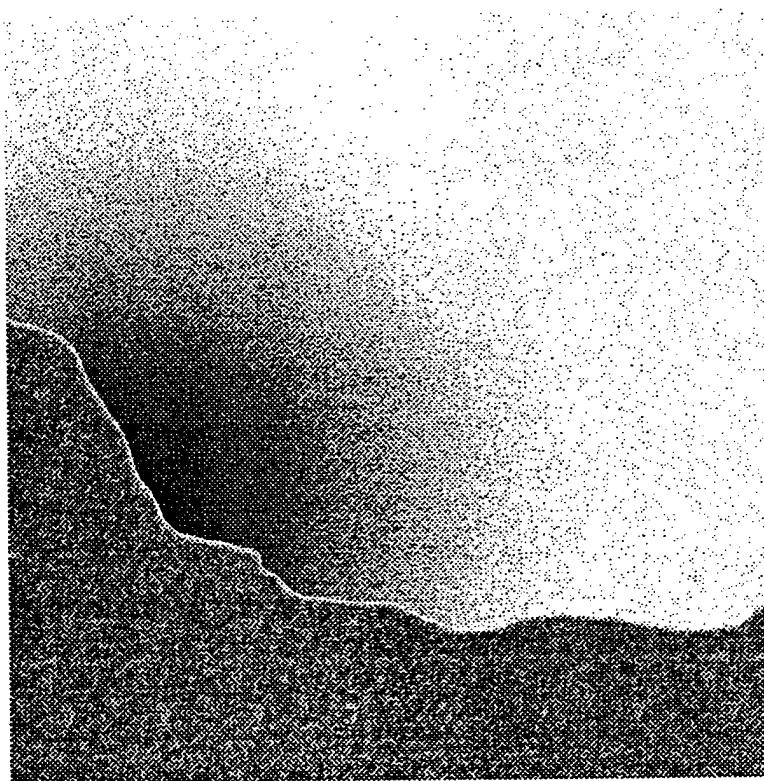


THERMAL DESORPTION: A TECHNOLOGY REVIEW



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1 Introduction

The development of new and innovative technologies to treat hazardous wastes is prompted by the extreme costs associated with remediating contaminated sites. In the United States, the cost of remediating both the Superfund and Resource Conservation and Recovery Act (RCRA) sites is estimated at \$750 billion (Wilson et al., 1994). Clearly these high costs encourage companies to develop more cost-effective methods of treating wastes.

One such innovative technology is thermal desorption, which heats soils, sediments, and sludges to volatilize any contaminants present. Briefly, thermal desorption units consist of a unit to heat the soil and a unit to treat the gases generated during this process (these elements will be discussed in more detail later). Thermal desorption is either classified as low temperature thermal desorption (90 to 320 °C) or high temperature thermal desorption (320 to 560 °C), depending on the soil temperature during the process (FRTR, 1997). Typically, the gases are either combusted or condensed and recycled, depending on the specific thermal desorption unit in place (Anderson, 1993).

This technology has received increased attention in recent years through the US Environmental Protection Agency's (EPA) Superfund Innovative Technology Evaluation (SITE) program, which allows vendors to demonstrate remediation technology at actual hazardous waste sites (Bellandi, 1995). Several vendors have developed and demonstrated their thermal desorption units under this program, thereby giving a means of assessing the performance of the technology. Prior to this, however, it is important to understand desorption processes and thermal desorption technology, so these topics will

be discussed first. Then, the performances of thermal desorption units and their ability to adequately protect worker safety will be discussed.

2 Desorption Processes

The key to understanding thermal desorption units and their performance is understanding desorption processes because they are the driving forces for the technology. Several factors influence desorption processes, including temperature, soil porosity, age of the contaminant, and soil moisture content.

The effect of temperature on desorption has been studied by several researchers, including Lighty et al. and El-Shoubary et al. Each group found that temperature was an important parameter in desorption, with Lighty determining that temperature was “the most important parameter” affecting the desorption of contaminants from soil (Lighty et al., 1990). El-Shoubary studied the desorption of polychlorinated biphenyls (PCBs) and motor oil from porous materials and determined that each contaminant had an onset temperature below which desorption would not take place (El-Shoubary et al., 1994). For the desorption of PCBs from porous material (granular activated carbon in this case), the onset temperature was determined to be 350 °C (El-Shoubary et al., 1994).

El-Shoubary et al. also investigated the effect soil porosity has on desorption in their experiments by utilizing different soil matrices. They performed their studies on soils with significant pore structures such as clays and activated carbon compounds, then performed similar experiments on soils where the pore structure was destroyed through superheating (El-Shoubary et al., 1994). Through these studies, the researchers found that desorption does depend on porosity—as pore structure increased, the onset temperature increased (El-Shoubary et al., 1994). Other researchers also studied this

process and found that contaminants quickly desorbed from non-porous materials, but desorbed more slowly from porous materials. This effect was attributed to the mass transfer resistance through the pores and increased contaminant binding due to the higher surface area of the porous materials (Lighty et al., 1989; Wilson et al., 1994; Connaughton et al., 1996).

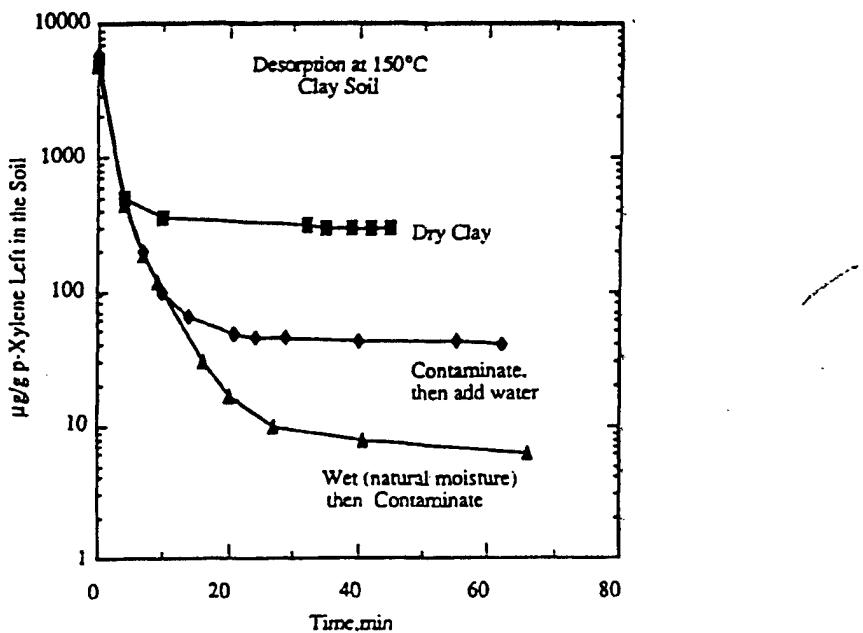
The effect of the age of the waste is not as clear because of disagreement in the literature. In their studies, Connaughton's group determined that the age of the waste played a significant role in determining the desorption rates. They evaluated soils contaminated with naphthalene for days and weeks and compared the results with soils exposed for thirty years. Through these experiments, it was determined that a region of irreversible sorption exists. For the freshly contaminated soils, the final 10 to 20 percent of the sorbed mass was resistant to desorption, while this percentage increased to 20 to 40 percent for the "old" soil. These results indicate that there is a region where desorption is resisted and that increased exposure time leads to an increased mass fraction in the rate-limited phase. Connaughton postulated that this rate-limited desorption occurs because the contaminant migrates deep into the pore structure and takes longer to diffuse to the surface where it can desorb (Connaughton et al., 1996).

The results of other researchers do not completely agree with this assertion, however. Lighty et al. studied the desorption of *p*-xylene from soils that were contaminated for one day, six months, and one year and found very little difference in desorption rates (Wilson et al., 1994). While this appears to contradict the work of Connaughton, and Wilson dismisses the notion of longer diffusion rates, it is important to look at the time scales involved. Connaughton studied soil that was contaminated for

thirty years, which is considerably longer than one year. With this in mind, it seems that Lighty's results do not contradict Connaughton's because they cannot be extrapolated from one year to thirty years in a meaningful way.

The final factor affecting desorption processes is soil moisture content, which plays a somewhat tricky role in thermal desorption systems because it is both beneficial and detrimental. Moisture plays two beneficial roles in thermal desorption—steam distillation and competition for binding sites. Steam distillation occurs when the water in the soil is volatilized and strips the contaminant with it. Research on *p*-xylene showed that contaminated soil with a moisture content of 10 percent desorbed two orders of magnitude more contaminant than contaminated dry soil (see Figure 1). This effect was augmented by the fact that the water took up binding sites on the soil that would otherwise have sorbed the *p*-xylene (Wilson et al., 1994).

Figure 1. Desorption of *p*-xylene from clay with varying moisture content (Wilson et al., 1994).



While soil moisture content may aid in the desorption of contaminants, it is not necessarily beneficial in commercial thermal desorption applications. As the water content of the soil increases, the energy demands to heat and volatilize the water increase, thereby increasing the treatment costs. Clearly, a balance must be struck between the benefits and costs of soil moisture. In most cases, a soil moisture content of eight to twelve percent is considered ideal for commercial thermal desorption units (Rosta et al., 1994).

3 Application of Thermal Desorption Technology

Typically, contaminated sites contain contamination in many media—soil, sludge, sediment, water, and groundwater. When considering any treatment technology, it is essential to determine the applicability of that technology to the contaminants on site. With this in mind, it is fruitful to discuss the media that can be treated by thermal desorption and the contaminants that can be efficiently removed by the technology.

3.1 Contaminants and Media

Thermal desorption units are designed to work with contaminants that can easily be desorbed from soils, sediments, and sludges (Rasmussen, 1994). These systems are effective for removing volatile organic compounds (VOCs), semi-volatile organic compounds (SVOCs), polycyclic aromatic hydrocarbons (PAHs), fuels, and PCBs (Bellandi, 1995; FRTR, 1997; Stepp, 1995). It should be noted, however, that the effectiveness of the treatment will depend on site-specific and chemical-specific parameters, giving the technology “varying degrees of effectiveness against the full spectrum of organic contaminants (FRTR, 1997).”

3.2 *Limitations*

While thermal desorption is applicable to a wide range of organic contaminants in various solid media, there are several factors that may limit its effectiveness. The possible problems are:

- (1) Feed particle sizes greater than two inches, which can increase the cost;
- (2) High moisture content, which may require dewatering;
- (3) Highly abrasive feed, which may damage the processor unit; and
- (4) High humic content soils, which may lead to increased retention time due to increased binding of contaminants (FRTR, 1997).

While one or all of these problems can be present to some degree, the goal is to manage each one to create a fairly homogenous feedstock for the thermal desorption unit. Overall, the goal is treating contaminated solids with a consistent contaminant concentration, moisture content, and particle size (Bellandi, 1995).

Attempts to achieve this consistency occur while pre-treating the waste prior to feeding it into the desorption unit. Since this is typically the first step in the treatment process, it will be discussed first, followed by descriptions of the various thermal desorption units available and the off-gas and solids treatment options available.

4 Waste Pretreatment

From the previous discussion on desorption processes and applicability, it is apparent that soils, sludges, and sediments that are to be treated with thermal desorption must meet certain pretreatment standards. Most notably, these feedstocks must be treated to attain a specific moisture content, particle size, and contaminant concentration.

4.1 Moisture Content

As stated in Section 2, a soil moisture content of eight to twelve percent is considered ideal when treating soils with thermal desorption, but many soils and sludges have more moisture. In order to achieve this range of soil moisture content, moisture must be removed from wet materials. This process is generically referred to as dewatering, and can be accomplished through several methods, including air drying, mixing with drier materials, and mixing with treated fines (Anderson, 1993).

One system that mixes treated fines with the feedstock is employed by Clean-Up Technologies. In their system, particles removed in the off-gas treatment system are returned to the primary treatment unit to be added to the feedstock (Rosta et al., 1994). This has the additional advantage of recycling some of the heat, since the fines are still significantly above ambient temperature. Another alternative was implemented by Retec when they integrated a sludge dewatering unit into their thermal desorption system, which allows raw sludge to be pumped into the thermal desorption unit without first being dewatered (Abrishamian et al., 1992). This integral unit eliminates the time and some of the costs associated with the other methods of dewatering, especially air drying, which can be time-consuming.

4.2 Particle Size

In trying to determine the effect of particle size on thermal desorption, Keyes et al. (1994) found that smaller particles were decontaminated more quickly than larger particles. When applied to thermal desorption systems, it is clear that the particle size must be maintained roughly smaller than two inches as discussed earlier. Typically, the soil feed unit will serve to screen out larger particle and break up clumps of particles

through agitation (Bellandi, 1995; McAdams, 1994). The larger particles may either be crushed and returned to the soil feed unit or cleaned individually.

4.3 *Contaminant Concentration*

At first glance, maintaining a consistent contaminant concentration might not seem too important, but it is essential to maintaining consistent operation of the thermal desorption unit. Large variations in contaminant concentration can lead to a compromise in treatment efficiency and possibly unacceptable air emissions (Bellandi et al., 1995). To prevent such an occurrence, the feedstock must be monitored to ensure its characteristics are fairly consistent. When a highly contaminated feedstock is encountered, the easiest method to lower its concentration is to mix it with a material with a lower contaminant concentration (Anderson, 1993).

5 Thermal Desorption Units

Once the waste feed is pretreated, it is ready to enter the thermal desorption unit. With a basic understanding of desorption processes and the applicability of thermal desorption, it is possible to review the various technologies available for thermal desorption units. While there are several technologies currently in use, thermal desorption units fall into a few broad classes: thermal blankets, rotary dryers, heated screws, and fluidized bed dryers. Alternatively, there are new technologies used in thermal desorption systems that will be discussed briefly. Each of these units requires off-gas treatment systems, and some require treatment of the soil residuals.

5.1 *Thermal Blankets*

Thermal blanket systems are modular treatment units that are used for *in situ* treatment of contaminated surface soil. One such system is used to treat soil

contaminated with PCBs and hydrocarbons to a depth of 15 cm with 2.4 m × 6.1 m modules that heat the soil with resistance heaters requiring 90 kW of energy per blanket. In a study of this system, Iben et al. found the blanket operated at 815 to 925 °C and that it took 20 to 24 hours for the soil to reach 200 °C to a depth of 15 cm (Iben et al., 1996). These systems are of limited utility, however, because they are only able to treat surface contamination, thereby limiting their implementation.

Another thermal blanket system also uses resistance heaters, but it is able to treat contaminated soils to a depth of 91 cm. This system is also used on volatiles, semi-volatiles, and PCBs. While this system offers improved performance over the one studied by Iben, it still cannot treat contaminated soil below fairly shallow depth. For these cases, thermal desorption units utilizing excavation must be implemented.

5.2 *Rotary Kilns (Rotary Dryers)*

Rotary kilns are large cylinders that rotate along their longitudinal axis at 0.5 to 2 rpm (LaGrega et al., 1994), although some units rotate as fast as 10 rpm (Bellandi, 1995). Typically, the kilns are sloped at 1° to 2° downward from the feed end to move the waste horizontally through the dryer. While moving through the dryer, the contaminated feed is heated along the way and the contaminants are volatilized, exiting the dryer as off-gas. The remaining solids are discharged from the dryer for disposal or further treatment as necessary.

The dryers used for thermal desorption are essentially identical to those used for incineration with the exception that they may be either direct-fired (see Figure 2) or indirect-fired (see Figure 3). In direct-fired systems, the contaminated media comes in contact with the flame, which is how incinerators operate. With indirect-fired systems,

the flame heats the rotating shell and does not contact the media directly (Anderson, 1993). The distinction between direct- and indirect-fired systems is important because of two primary concerns: permitting requirements and PCB treatment.

Since direct-fired rotary dryers are analogous to incinerators, they are considered incinerators by EPA and require permitting as such (Stepp et al., 1995). This is certainly undesirable because of the significant cost and time associated with the permitting

Figure 2. Direct-Fired Rotary Dryer (modified from LaGrega et al., 1994).

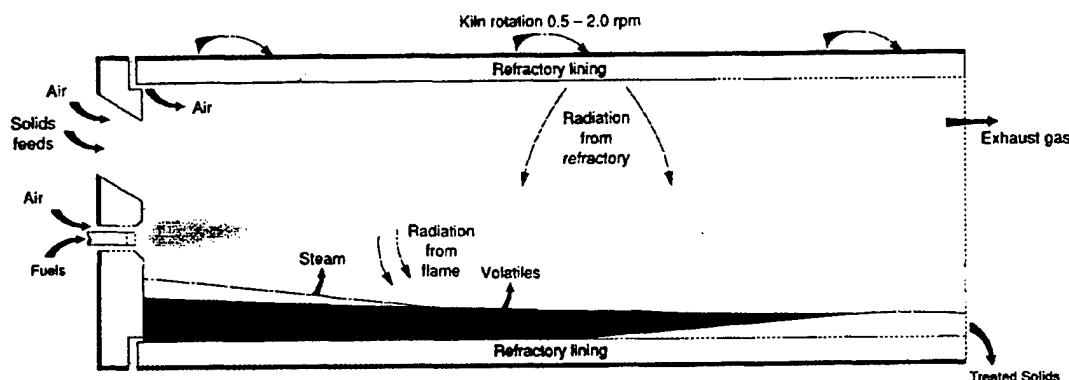
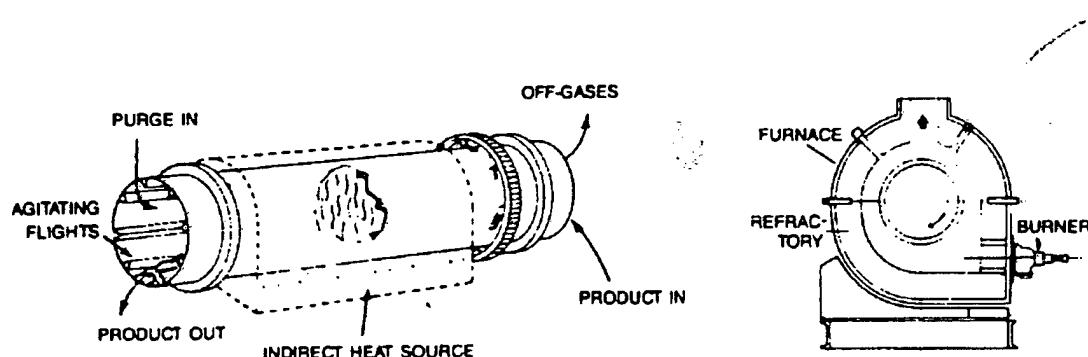


Figure 3. Indirect-Fired Rotary Dryer (Wilson et al., 1995).



process, but there is an additional reason for concern. Direct-fired rotary dryers are more likely to create Products of Incomplete Combustion (PICs) when treating wastes contaminated with PCBs (O'Brien et al., 1995; Wilson et al., 1994). PICs include such compounds as chlorodibenzo-*p*-dioxin (CDD) and dibenzofurans (CDF), which are a major health concern and are under tight regulatory scrutiny (Bellandi, 1995).

Due to this limitation of direct-fired rotary dryers, they are not typically used to treat wastes containing PCBs. Additionally, the increased permitting requirements discourage their use. They are beneficial in some systems, however, because the direct firing can lead to partial oxidation of some of the contaminants. This has the advantage of lowering the requirements for off-gas treatment.

5.3 *Heated Screws*

Heated screw thermal desorption units utilize the feed system to heat the contaminated feedstock. The screws typically use hot oil, molten salt, or electric resistance heaters to heat the screw that then heats, mixes, and conveys the feedstock in an enclosed shell or trough (FRTR, 1997; Wilson et al., 1994). As with rotary dryers, these systems may be either direct or indirect-heated systems. In direct-heated systems, electrical resistance heaters are placed on the outside of the screw and they come in contact with the feedstock. In indirect-heated systems, the hot fluid or heaters are contained inside the screw and the heat is conducted through the screw to heat the feedstock (Svedala, 1997).

There are a few things that must be considered when choosing between the various types of heated screw systems. For starters, heated screws have the advantage of a larger heat transfer surface than other systems, thereby lowering the energy

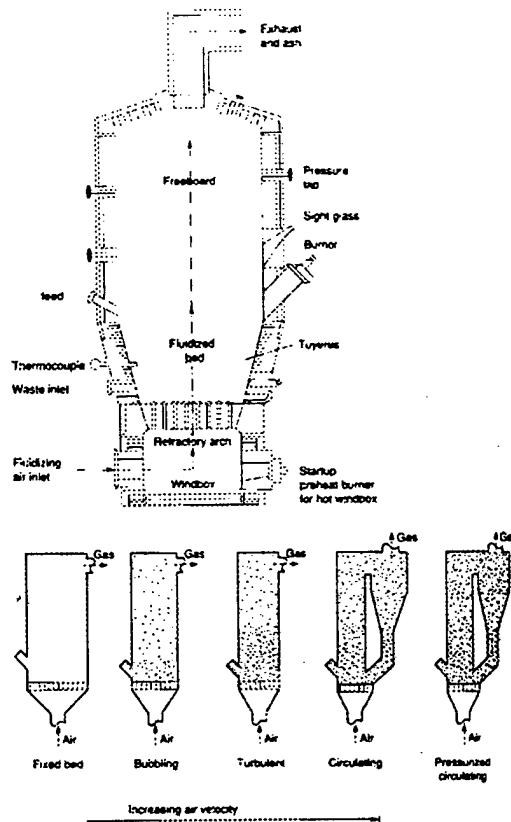
requirements for the system (Wilson et al., 1994). This is not without its drawbacks, however. In indirect-heated systems using hot oil or molten salt, the maximum temperature of the system is limited by the heat capacity of the fluid. From a practical standpoint, hot oil systems are limited to feedstock temperatures of 275 °C, which makes them unsuitable for PCB-contaminated wastes, while molten salt systems are limited to temperatures of 400 °C (Wilson et al., 1994).

When using direct-heated systems, the temperature of the feedstock is limited by the power output of the heater elements. Successful systems have been demonstrated that operate at feedstock temperatures of 1100 °C, which pushes them into the realm of incinerators (Wilson et al., 1994). Obviously, which heated screw system is chosen will depend on the necessary operating temperature, with the hot oil systems being used for low boiling point contaminants, molten salt systems for intermediate boiling point contaminants, and resistance heating systems for higher boiling point compounds such as PCBs.

5.4 *Fluidized Bed Dryers*

These thermal desorption units utilize high temperature gases to treat the contaminated feedstock. In fluidized bed dryers, the feedstock is injected into a fluid hearth where hot gases enter and hold the feedstock in suspension (LaGrega et al., 1994). These systems are somewhat complicated by the need to adjust the air flow until the contaminated media achieves neutral buoyancy, but they have the advantage of turbulent mixing, which greatly enhances the heat transfer in the system (Wilson et al., 1994). Figure 4 illustrates a typical fluidized bed unit along with variations depending on the incoming air velocity.

Figure 4. Fluidized Bed Dryer (LaGrega et al., 1994).



5.5 Alternative Technologies

Not surprisingly, there are many other ways to heat contaminated soils to promote desorption. While there are many technologies at the pilot-scale stage, only those that have been utilized on actual cleanup projects will be discussed. The two technologies that meet this criterion are waterfall heating and infrared heating.

Enviro-Klean Soils, Inc. uses a proprietary thermal heating unit to take advantage of waterfall heating. In their system, contaminated soil is continuously fed in front of a propane-fired flame, thereby achieving direct heating of the soil. This achieves faster desorption of the contaminants from the soil and is suitable to remove VOC

contamination. This technology is somewhat limited in its application, however, as it is not designed to treat waste contaminated with PCBs, dioxins, pesticides, cyanides, or corrosives. Also, the system cannot handle clay soils with over five percent moisture or regular soils with over 20 percent moisture (USEPA, 1996(b)).

The second alternative technology of note is infrared heating, which is utilized in Westinghouse's Thermal Desorption Unit (TDU) and McLaren/Hart Environmental Engineering's IRV-100 and IRV-200 units. The Westinghouse system uses infrared thermal heating rods and a residence time of ten to 20 minutes to treat a range of volatile compounds (O'Brien et al., 1995). McLaren/Hart's system directly heats aluminized steel tubes to 590°C in a propane-fired combustion chamber. This high temperature induces the tubes to emit electromagnetic radiation in the infrared spectrum, which then heats the soil. The system maintains a residence time of two to three hours, and, as with other thermal desorption units, a soil moisture content above 20 percent will hinder performance (USEPA, 1996(b)).

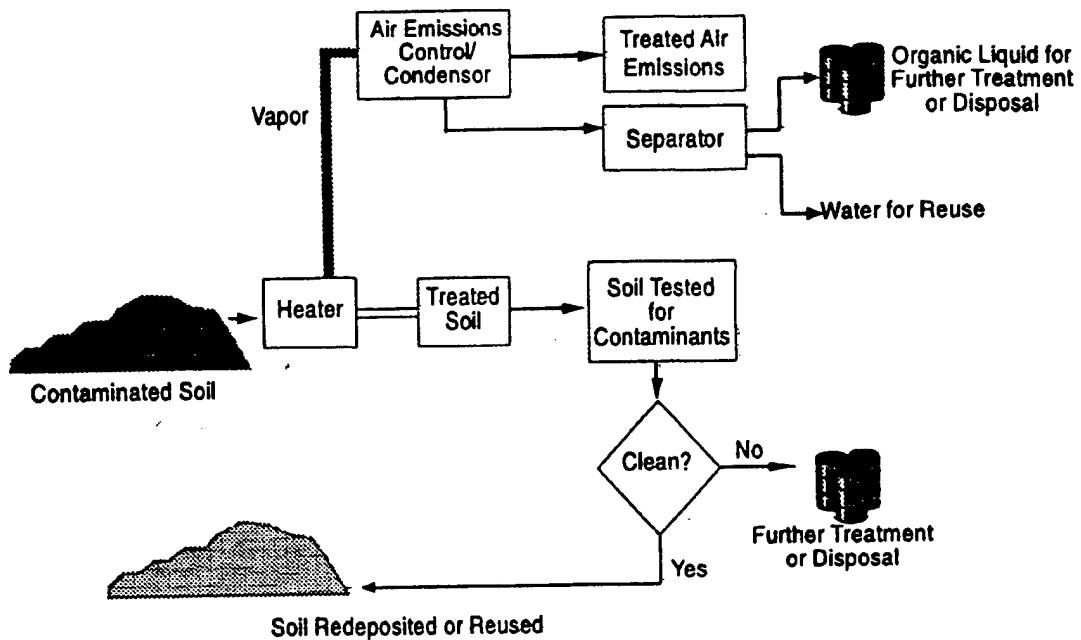
While this range of technologies offers a variety of treatment options, rotary kilns are by far the most common type of thermal desorption systems in use today. A look through Appendix B demonstrates this fact because better than 60 percent of the vendors listed use rotary kiln technology in their thermal desorption systems.

6 Off-Gas Treatment

One thing common to thermal desorption technologies is that the contaminants leave the thermal desorption units as gas, which must then be treated (Figure 5). The two principle means of treating these gases are through destruction or condensation. Common to both types of off-gas treatment are systems to control acid gases and

particulate, which will be discussed first, followed by destruction technologies and condensation technologies.

Figure 5. Thermal Desorption Process (USEPA, 1994).

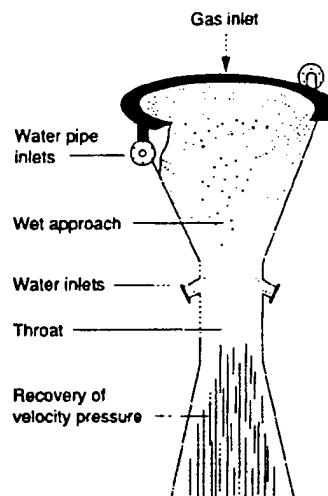


6.1 Acid Gas and Particulate Control

Acid gases may or may not be present in the off-gas from thermal desorption units depending on the waste characteristics, fuel used, and system setup. While thermal desorption systems do not usually generate large quantities of acid gases, hydrogen chloride and sulfur dioxide may be present, and they are removed with venturi scrubbers or wet scrubbers (Anderson, 1993; Krukowski, 1992; O'Brien et al., 1995). Venturi scrubbers (see Figure 6) contain a venturi throat where the cross sectional area is reduced and flow velocities increase to 60 to 180 m/sec, which increases mixing and acid gas

removal. This throat section utilizes 8 to 45 L of water per 28 standard cubic meters of off-gas and has a pressure drop of 10" to 30" w.g. (Anderson, 1993).

Figure 6. Venturi Scrubber (LaGrega et al., 1994).



While the venturi scrubbers have been somewhat successful, the large pressure drop required lowers their energy efficiency (LaGrega et al., 1994). Additionally, the acid gas mixture tends to erode the venturi throat, a phenomena that is exacerbated by the high flows and turbulence in the throat section (Anderson, 1993). Despite this, these systems have been used to control acid gases because they have the benefit of removing 5 μg particles (Anderson, 1993).

Where venturi scrubbers use mechanical means to remove acid gases, wet scrubbers utilize chemical means by promoting acid-base neutralization reactions. These systems use an alkali reagent in slightly greater than stoichiometric amounts to neutralize the acid gases in treatment stacks. Ideally, these scrubbers operate in a pH range between five and seven to prevent the formation of calcium carbonate and sodium bicarbonate, which foul the scrubber internals (Anderson, 1993).

Particulate removal is required of all thermal desorption units, whether they contain acid gases or not. Several technologies are available to address particulate removal to the EPA's regulatory level (currently 180 mg/dscm), but the most common methods in use are cyclone separators and baghouses (Krukowski, 1992; Rosta et al., 1994).

Cyclone separators are common in many industries for removing large particles. These devices utilize inertial separation to remove particles from a gas stream. Currently, only dry cyclones are in use in thermal desorption units, and these systems direct the gas stream into a vortex flow pattern that forces larger particles ($> 15 \mu\text{m}$) into the side walls where it will eventually fall into the collector unit at the bottom of the separator (Anderson, 1993). Since these systems work best at removing larger particles, they are commonly used in series with other particulate removal systems, such as baghouses.

After leaving the cyclone separator, the off-gas is frequently directed to a baghouse, which is an enclosure containing several fabric filters. These filters remove particulate matter smaller than $10 \mu\text{m}$ and are even efficient at removing particulate smaller than $1 \mu\text{m}$ (Anderson, 1993). Several factors enter into designing these systems, with filter life, cleaning, and removal efficiency chief among them. Additionally, different filter media have different operational parameters as shown in Table 1. When properly designed, these systems prove effective at removing particulate to below regulatory limits, with O'Brien & Gere Engineers, Inc. utilizing a baghouse that lowered particulate emissions to 45 grains/dscm (Bellandi, 1995).

Table 1. Baghouse filter fabrics suggested operating temperatures (Anderson, 1993).

Fabric	Operating Temperature
Nomex	220 to 260 °C
Fiberglass	290 to 315 °C
Teflon	230 to 260 °C

6.2 *Destruction Technologies*

As the name implies, destruction technologies destroy the desorbed contaminants in the off-gas. The primary destruction technology used with thermal desorbers is incineration of the contaminants in an afterburner chamber, but catalytic oxidation has also been used successfully. These systems will also have some form of particulate control and acid gas control, depending on the waste feed (Wilson et al., 1994).

Afterburners, also called secondary combustion chambers, treat off-gases by oxidizing the contaminants at high temperatures. These systems operate at 760 to 980 °C with residence times ranging from 0.5 to 2.0 seconds (Anderson, 1993; Bellandi, 1995). The afterburner can achieve removal efficiencies of 99.9 percent, but since it functions much like an incinerator, it requires permitting as an incinerator (Bellandi, 1995; Wilson et al., 1994).

Another destruction technology involves catalytic oxidation of off-gases to remove contaminants. The function of catalytic oxidizers is similar to afterburners, except the organic contaminants are maintained at a temperature below where they will spontaneously oxidize, but above where they will oxidize in the presence of a catalyst. The catalyst is usually a noble metal such as platinum or palladium. These systems are advantageous because they operate at lower temperatures than afterburners, but there are a couple of limitations on their use. First, a sudden increase in organic concentration may

lead to a temperature increase that can destroy the catalyst and support structure. Second, elements such as chlorine, sulfur, and vanadium can poison the catalyst and lower their effectiveness. Due to these limitations, catalytic oxidizers are mainly used in systems with fairly constant organic concentrations in the off-gas and that do not contain appreciable quantities of the poisoning elements (LaGrega et al., 1994).

6.3 *Condensation Technologies*

An alternative to destroying the desorbed contaminants is to condense them for later recycling or treatment (these options are discussed in Section 6.4). This is accomplished through condensers and scrubbers, which are followed by carbon adsorption units to remove any non-condensable hydrocarbons and mist eliminators to remove any residual moisture (Abrishamian et al., 1992; O'Brien et al., 1995; Rasmussen, 1994).

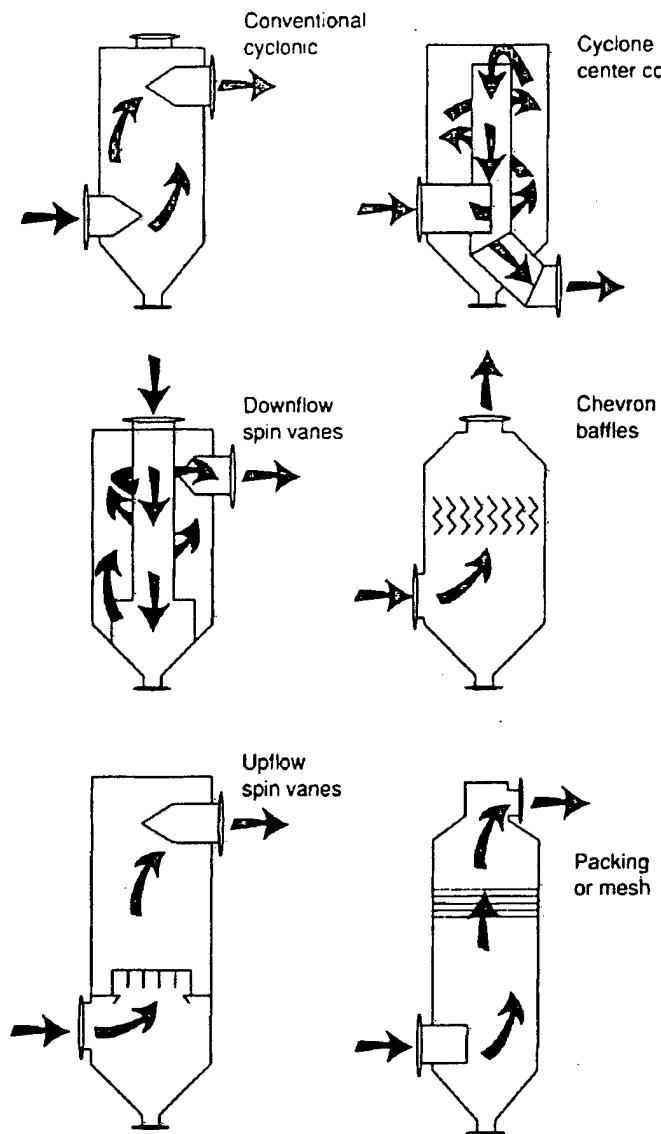
Condensers may operate in a variety of ways, but the primary goal is to lower the gas temperature to condense any vapors. One method uses direct contact of the off-gas with a condensed oil and water stream that recirculates through a heat exchanger to maintain its temperature (Rasmussen, 1994). The second method involves two steps. The first step uses a scrubber in which the off-gas is filtered through water to cool the gas to its saturation temperature, thereby removing up to 30 percent of the vaporized organics and much of the water vapor. A condenser is utilized in the second step where cool air is used to lower the off-gas temperature to approximately 5 °C over ambient temperature, thereby removing the bulk of the entrained organics and water vapor (Anderson, 1993).

While condensers may operate quite efficiently, they will not remove all the contaminants in the off-gas. This requires the addition of carbon adsorption units to the off-gas treatment system. The design of carbon adsorption units will vary depending on the waste to be removed, but the two important parameters to consider are the empty bed contact time and the superficial gas velocity. The definition of the empty bed contact time is the "ratio of empty bed volume to the volumetric gas-flow rate through the bed [seconds]," while the definition of superficial gas velocity is the "ratio of volumetric gas-flow rate to the cross-sectional area of the bed [m/sec] (Anderson, 1993)." Typical values of these parameters are 2.0 to 4.2 seconds and 0.30 to 0.46 m/sec, respectively.

Carbon adsorption units operate by providing a high surface area for reaction with organic contaminants. Any non-condensable contaminants that pass through the condensation stage are adsorbed to the activated carbon and prevented from escaping to the atmosphere. The carbon adsorption unit may also be used as a finishing step to remove trace amounts of organic contaminants prior to venting the off-gas (O'Brien et al., 1995).

Whereas carbon adsorption units operate to remove residual hydrocarbons in the off-gas, mist eliminators operate to remove residual moisture in the off-gas. Mist eliminators add a tortuous path of baffles to the off-gas flow, on which the moisture droplets impact (see Figure 7). The water droplets coalesce on the baffles and drain through gravity to be removed from the system (LaGrega et al., 1994).

Figure 7. Typical Mist Eliminator Configurations (LaGrega et al., 1994).



6.4 Liquids Treatment

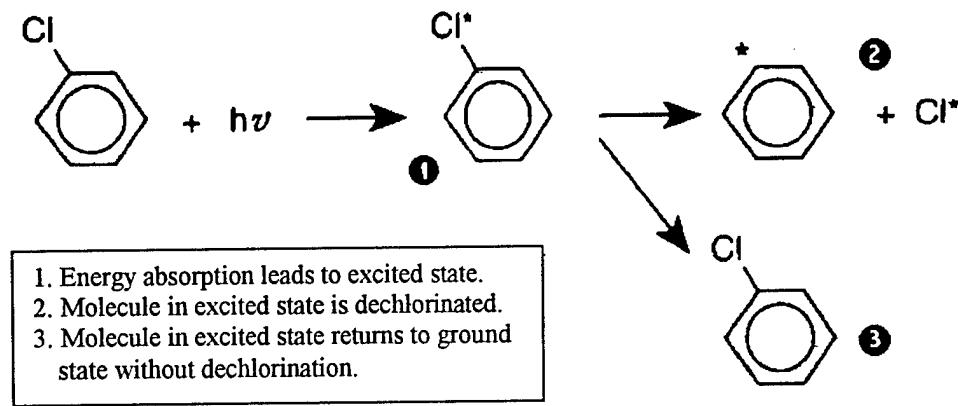
When bulk contaminants are recovered with condenser units, these liquids must be managed properly. The primary options available in this case are recycling and treatment of the waste prior to disposal.

By recovering the contaminants on-site at petroleum processing facilities, the thermal desorption system does not require a RCRA Part B permit for Treatment, Storage, and Disposal facilities, which greatly reduces the permitting costs. A system implemented by Waste-Tech Service, Inc. at Amoco's Texas City refinery utilizes this exemption and pumps the recycled hydrocarbons back to the refinery for processing (Rasmussen, 1994). This treatment method also lowers refinery waste volumes by two-thirds and lowered the cost of disposal (compared with use as an auxiliary fuel in cement kilns) by 37 percent (Broussard-Welther, 1992).

Obviously, this is a great advantage when employed at refineries, but it has also proven to be cost effective at Superfund sites. Seaview Thermal Systems used its HF-6 thermal desorption unit at a Superfund site to recover coal tar, coal oil, and traces of aromatic hydrocarbons. After the condensation step, the recovered oil was sold to the petroleum industry for processing into fuel (Valenti, 1994). In this instance, since treatment permits were already required, the money made selling the recovered product was essentially a bonus and made recycling worthwhile.

Alternatively, the condensed contaminants may be treated prior to ultimate disposal. One method employed with thermal desorption involves dechlorination to reduce the toxicity of the compounds prior to disposal (Page, 1997). Two common types of dechlorination are photolytic and reductive. Photolytic dechlorination occurs when ultraviolet light strikes a chlorine-containing molecule and cleaves the bond, removing the chlorine. This process is shown graphically in Figure 8.

Figure 8. Photolytic Dechlorination of Monochlorobenzene (Bellandi, 1995).

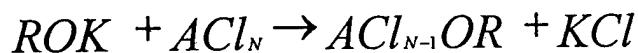


Reductive dechlorination, on the other hand, occurs when alkali-metal hydroxide reagent is mixed with the contaminant to remove chlorine atoms from the contaminant. This process is shown for potassium hydroxide with a dimethyl sulfoxide (DMSO) catalyst in Equations 1 to 3 below:

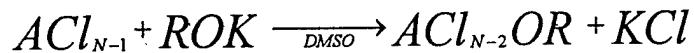
Equation 1



Equation 2



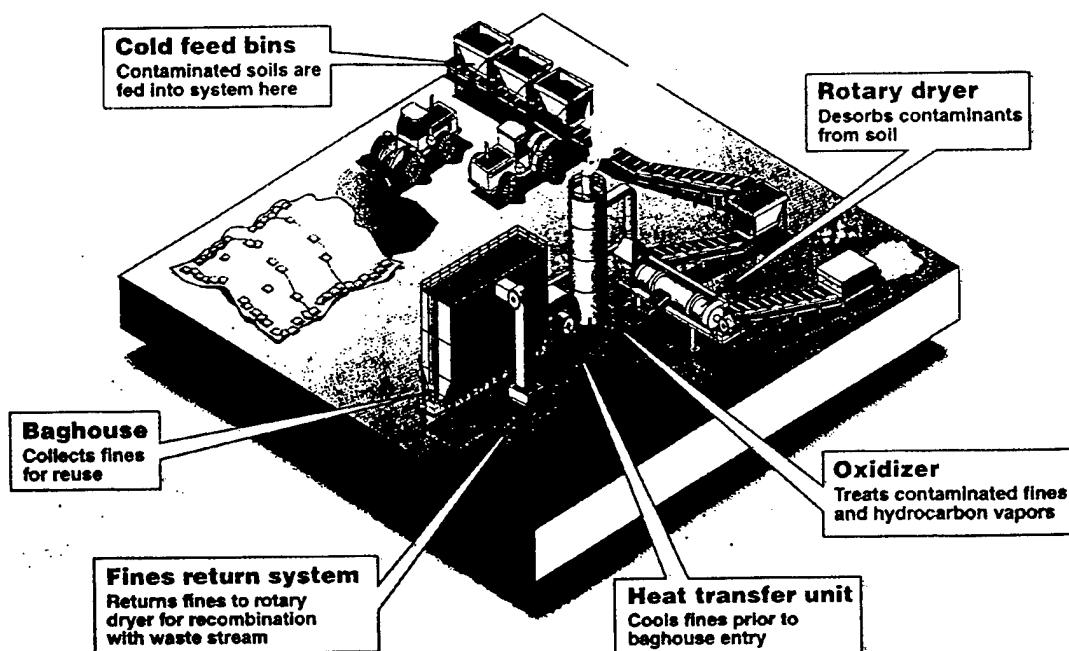
Equation 3



Typically this process occurs in a batch reactor with the attendant emissions controls and monitoring equipment to prevent atmospheric releases of contaminants (Bellandi, 1995).

Combined, the thermal units and off-gas treatment equipment comprise a thermal desorption system. Figure 9 illustrates how these parts of the system fit together in a rotary kiln system with an afterburner.

Figure 9. Schematic Representation of Rotary Kiln System with Afterburner (Rosta et al., 1994).



7 Solids Treatment

Thermal desorption removes contaminants from soils, sludges, and sediments, leaving solid soil material behind after treatment. These solids, whether containing residual contamination or not, must be treated as part of the remediation process (see Figure 5). Typically, non-contaminated soils are backfilled on-site with minimal treatment that includes the addition of moisture to keep dust down and the addition of nutrients to support plant growth (Campino et al., 1990; Rosta et al., 1994).

When soils contain residual contamination, which may be present because thermal desorption is not effective at removing heavy metal contamination (with the exception of mercury), additional treatment methods are commonly used on the solids (USEPA, 1994). This process of using multiple treatment methods at a site is often referred to as the treatment train, and in the US government's fiscal year 1994, the thermal desorption treatment train used solidification-stabilization four times and dechlorination once (see Section 6.4) (Fielder et al., 1996). In previous years, solidification-stabilization was used five times and off-site disposal in hazardous waste landfills was used four times (see Table 2) (USEPA, 1996(a)). (Since the latter practice is discouraged by current Superfund amendments, it will not be discussed further (42 USC § 9621(b)(1)).

Table 2. Secondary Treatments for Residual Solids by Fiscal Year.

FISCAL YEAR	SECONDARY TREATMENT METHOD			REFERENCE
	Solidification- Stabilization	Dechlorination	Offsite Disposal	
94	4	1		Fielder et al., 1996
93	1		1	USEPA, 1996(a)
92			2	USEPA, 1996(a)
91	1	1		USEPA, 1996(a)
90	2			USEPA, 1996(a)
89				USEPA, 1996(a)
88				USEPA, 1996(a)
87	2			USEPA, 1996(a)
86			1	USEPA, 1996(a)

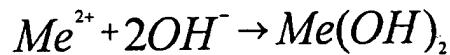
7.1 Solidification-Stabilization

Solidification-Stabilization seeks to lower the risk from contaminants by reducing their mobility and lowering their toxicity. Specifically, solidification encompasses technologies that change the physical characteristics of a waste to make it less mobile in

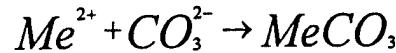
the environment, while stabilization refers to technologies that convert the waste into less toxic forms (Woodside, 1993).

Lime-based, cement-based, and pozzolanic solidification-stabilization processes are common when dealing with hazardous waste. In lime-based systems, lime, Ca(OH)_2 , and water are added to the soil to immobilize metal contamination. Chemical reactions between the waste and lime lead to the formation of hydrates of calcium silicate, calcium alumina, or calcium-alumino silicate, thereby precipitating the metal ions in the waste (LaGrega et al., 1994; Woodside, 1993). Cement-based systems operate in a similar manner with the additive being portland cement (calcium, silicate, aluminum, and iron oxides), and the resulting compounds are insoluble hydroxide or carbonate salts:

Equation 4



Equation 5



that remain in the hardened cement structure after curing. Pozzolanic materials are similar to cement because they involve alumino-silicious material that forms a cementitious material when mixed with water and lime. The reactions resulting from this mixture will be those shown in Equations 4 and 5 (LaGrega et al., 1994).

These solidification-stabilization schemes have similar advantages. Since the materials are produced in large quantities for construction activities, one can achieve economies of scale and the technology is well known (Batchelor, 1997). Additionally, after treatment, the remaining material is a monolithic block that can be left on-site

without further intervention. Despite these advantages, other forms of solidification-stabilization are occasionally used.

Other common solidification-stabilization processes involve the use of thermoplastics and polymers. In the thermoplastic process, the waste material is blended with a molten thermoplastic material, which causes the waste to be contained in the plastic matrix. Typical materials are bitumen, asphalt, polyethylene, and polypropylene. When using the reactive polymer process, the waste is mixed with reactive monomers (urea-formaldehyde, phenolics, epoxides, polyesters, or vinyls) and with polymerizing catalysts to trap the waste in the organic matrix (Woodside, 1993). While these methods are applicable to heavy metal contamination, they are more expensive than lime-based, cement-based, and pozzolanic solidification-stabilization.

8 Operational Parameters

From the discussion on thermal desorption systems, it is obvious that they are fairly complex systems with many variables that must be controlled. When operating thermal desorption units, however, there are a few parameters that are of paramount importance to ensure proper waste treatment. These are temperature, residence time, sweep gas, and vacuum. Other considerations involving waste uniformity, moisture content, and soil size are discussed in Section 4.

8.1 Temperature

The temperature chosen for the thermal desorption unit depends on the waste to be treated and the thermal desorption unit being used. The ranges for the various technologies are shown in Table 3.

Table 3. Soil Temperatures for Various Technologies.

TECHNOLOGY	SOIL TEMP. (°C)	REFERENCE
Thermal Blankets	200	Iben et al., 1996
Rotary Dryer (direct-fired)	150 to 585	NTTC, 1997(b) USEPA, 1995(b) USEPA, 1995(d)
Rotary Dryers (indirect-fired)	120 to 620	NTTC, 1997(c) USEPA, 1995(c) USEPA, 1995(e)
Heated Screws	200 to 280	NTTC, 1997(d) USEPA, 1995(a)
Fluidized Beds	600	NTTC, 1997(a)

From the data, one can see that thermal blankets and heated screws are typically utilized in low temperature thermal desorption units (90 to 320 °C); fluidized beds are typically utilized in high temperature thermal desorption units (320 to 560 °C); and rotary dryers are often used in both low temperature and high temperature thermal desorption units.

The determination of what temperature to use is generally mandated by the contaminants present in the waste feed. As discussed in Section 2, temperature has a significant effect on the desorption of contaminants from soils, with contaminants exhibiting varying onset temperatures. When utilizing thermal desorption, the soil must be heated above the onset temperature of the contaminants. One might expect thermal desorption to occur successfully above the boiling point for the contaminants of interest, but this is not always the case. Generally, as the contaminants bind to the soil matrix, the temperature necessary to achieve desorption increases (Connaughton et al., 1993). To account for this, thermal desorption units are typically operated significantly above the boiling point of the contaminants of concern.

8.2 Residence Time

The solids residence time goes hand-in-hand with the operating temperature in determining the treatment efficiency of the thermal desorption unit. There is a distinct time-temperature tradeoff involved in designing systems because higher temperature means a lower residence time, but higher energy costs. In commercial systems, these tradeoffs must be balanced to determine the optimum residence time.

As with temperature, the residence time will vary depending on the contaminants present in the feedstock, with the values ranging from a low of five minutes to a high of ninety minutes. An overview of this range is shown in Table 4, which illustrates the variation in residence time with technology and contaminant.

Table 4. Solids residence time vs. technology and contaminants.

TECHNOLOGY	CONTAMINANTS	RESIDENCE TIME (min)	REFERENCE
Rotary Kiln (indirect-fired)	VOCs, SVOCs, PAHs, pesticides, inorganic metals	5	USEPA, 1995(c)
Rotary Kiln (direct-fired)	Halogenated VOCs and PAHs	6	USEPA, 1995(b)
Rotary Kiln (direct-fired)	Organic-chlorine pesticides	15	USEPA, 1995(d)
Rotary Kiln (indirect-fired)	PCBs	30 to 40	USEPA, 1995(e)
Heated Screw	Halogenated and non-halogenated VOCs and PAHs	90	USEPA, 1995(a)
Thermal Blanket	PCBs	24 hrs	Iben et al., 1996

From Table 4, it is apparent that there is a wide range of residence times for thermal desorption systems. Generally, the residence time increases with the molecular weight of the contaminant, with PCBs having the longest residence times. Also, heated screws and thermal blankets have much longer residence times than rotary kilns. This

can be explained by the heat transfer properties of these systems. Heated screws tend to operate at lower temperatures, which means they require longer to heat the soil to the necessary temperature for desorption. Thermal blankets, on the other hand, suffer the disadvantage of large heat transfer resistances. Since these systems operate in situ, they must heat a large block of soil at one time instead of small batches as in other technologies.

When determining the appropriate retention time for a specific site and technology, the best method is to perform a treatability study. These studies generally involve bench scale tests to determine the feasibility of using thermal desorption as a treatment method, and they determine the optimum residence time and temperature for the contaminated matrix (Bellandi, 1995).

When utilizing rotary kilns, an additional calculation must be made once the residence time is known. Since these systems rotate at a fixed speed, the speed of rotation to achieve the desired residence time must be determined. This simple calculation can be performed by using Equation 6:

Equation 6

$$t = \frac{0.19L_r}{(rpm)(D)(S)}$$

Where: L_r = Length of kiln (m)

rpm = Kiln rpm

D = Kiln inner diameter (m)

S = Slope of kiln (m/m)

(Anderson, 1993)

When using this equation, it is important to note that the kiln rpm is typically the only variable that can easily be varied to achieve the desired residence time.

8.3 Sweep Gas

Thermal desorption units utilize a sweep gas to carry the volatilized contaminants from the primary treatment unit to the off-gas treatment unit. As with the operational parameters just discussed, which sweep gas to use depends on the system and the contaminants involved.

The easiest sweep gas to use is steam because it is generated from moisture in the soil. This is typically utilized in systems that involve an afterburner for treatment, but may also be used in systems involving contaminant recovery (O'Brien et al., 1995). Also, steam is necessarily used in direct-fired rotary kilns because the inert carrier gases discussed below would prevent combustion and the unit would not work. Steam is avoided, however, in systems containing PCBs because of the possibility of PIC formation during the desorption process. Since these contaminants are strictly regulated and undesirable from the public's viewpoint, preventing their formation is essential (Krukowski, 1992).

In systems treating PCBs and utilizing condensation technology to recover contaminants, nitrogen is a common carrier gas. Nitrogen is used to prevent combustion of the contaminants in the treatment unit, thereby preventing the formation of PICs (Abrishamian et al., 1992; Holden et al., 1989; McAdams, 1994). When using nitrogen as a sweep gas, the primary treatment unit is pumped full of nitrogen to remove any residual oxygen that might support combustion (McAdams, 1994). In these systems, the nitrogen is often recycled with only a small portion being vented at any one time (Holden et al., 1989). Also, while nitrogen is often considered problematic in incinerators because

of NO_x formation, there is no evidence of this posing a problem in thermal desorption units.

8.4 *Vacuum*

Thermal desorption units are operated at a slight negative pressure to prevent fugitive emission of contaminants from the system. Two examples of systems with vacuums are Westinghouse's TDU system and SoilTech's Anaerobic Thermal Processor (ATP). The Westinghouse system maintains a vacuum of 0.01 to 0.25 in w.c. and SoilTech's system maintains a vacuum of 0.08 to 0.12 in w.c. below atmospheric pressure (O'Brien et al., 1995; USEPA, 1995(c)). While these vacuums are not large, they succeed in minimizing the possibility of contaminants escaping the system and exposing on-site personnel.

9 Performance

Evaluating the performance of a treatment option involves looking at how well the method removes contamination, how much it costs, and how well it protects the safety of on-site workers. In this section, thermal desorption's effectiveness at removing contamination is evaluated, while its cost and safety issues will be reviewed in Sections 10 and 11 respectively.

Three main sources of information are available to evaluate the effectiveness of thermal desorption. First, the EPA's SITE program involves technology demonstrations where batch experiments are used to evaluate innovative technologies. Second, results from actual remedial projects may be used to evaluate a system's effectiveness. Finally, pilot tests published in scientific literature may be reviewed. These three sources of information will be evaluated in turn.

9.1 SITE Program Results

The EPA's Superfund Innovative Technology Evaluation program seeks to determine which emerging technologies are viable treatment options for Superfund sites. Information on four thermal desorption systems was available for review—from the units developed by Eli Eco Logic International, Inc. (fluidized bed), Maxymillian Technologies, Inc. (rotary kiln), OHM Remediation Service Corp. (indirect-fired rotary kiln), and Roy F. Weston, Inc. (heated screw).

Eli Eco Logic's thermal desorption system involves a fluidized bed filled with molten tin at 600 °C in a hydrogen gas atmosphere. The off-gases from the desorption unit are sent to a proprietary gas-phase chemical reduction unit where the contaminants are reduced. This system is designed to work on high-moisture content wastes containing PCBs; PAHs; chlorinated dioxins, dibenzo-furans, and solvents; chloro-benzenes; and chlorophenols (NTTC, 1997(a)).

During the SITE demonstration, which was performed at the Middleground Landfill site in Bay City, MI, the unit was used to treat waste contaminated with PCBs at an average concentration of 627 ppm. The demonstration was performed in two runs, and the results are tabulated below (NTTC, 1997(a)).

Table 5. Eli Eco Logic International, Inc.'s SITE Results

PARAMETER	RUN #	VALUE (%)
PCB Desorption Efficiency	1	93.5
	2	98.8
Hexachlorobenzene Desorption Efficiency	1	72.13
	2	99.998
PCB DRE for TDU and Reduction Reactor	Both	99.9999

The most important value to look at in this test data is the Destruction and Removal Efficiency (DRE) for PCBs. Current regulation requires that the DRE for PCBs be greater than or equal to 99.9999 percent, which this is (40 CFR § 264.343). Therefore, Eli Eco Logic's unit can be used to successfully treat PCB-contaminated waste.

Maxymillian Technologies, Inc. utilizes a rotary kiln operating at 320 to 540 °C with an afterburner operating at 870 to 1090 °C to treat VOCs, SVOCs, PAHs, coal tars, and cyanide. This unit was tested at the Niagara Mohawk Power Corporation's Harbor Point Site in Utica, NY on wastes contaminated with VOCs, PAHs, and cyanide. These wastes were tested in twelve runs to determine the DRE for xylene and naphthalene as Principle Organic Hazardous Constituents (POHCs). During the testing, the unit achieved a DRE of 99.99 percent for xylene on all twelve runs and a DRE of 99.99 percent for naphthalene on eleven of twelve runs (NTTC, 1997(b)).

When operating as an incinerator, as the afterburner does in this case, the unit is required by federal regulation to achieve a DRE for each chosen POHC of 99.99 percent or higher (40 CFR § 264.343). From the data presented, one can see that this was achieved for xylene each time, but was not achieved on one run for naphthalene. The data available does not discuss the reason for this discrepancy, but the difference may lie in the fact that naphthalene requires more oxygen than xylene to combust (LaGrega et al., 1994). Also, since the DRE was met for eleven of twelve runs, it is reasonable to assert that the unit can treat PAH-contaminated waste provided the operational parameters are optimized to ensure the DRE is met continuously.

The X*TRAX™ system offered by OHM Remediation Services Corp. is another rotary kiln unit, but this system operates at temperatures ranging from 200 to 650 °C and

recovers the volatilized contaminants instead of destroying them in an afterburner. This unit is also used to treat PCBs, SVOCs, VOCs, and PAHs, but it additionally will treat halogenated and non-halogenated solvents, pesticides, herbicides, and mercury (NTTC, 1997(c)).

This unit was used to treat PCB-contaminated waste at the Re-Solve, Inc. Superfund site in Massachusetts with positive results. X*TRAX™ achieved a PCB removal efficiency of 99.95 percent and attained the treatment standard of 25 milligrams per kilograms of treated soil. Since this is a low temperature thermal desorption unit with an inert nitrogen carrier gas, PICs were not formed in the unit. Also the total organic emissions from the unit were less than one gram per day, and PCBs were not observed in the vent gases (NTTC, 1997(c)). These results indicate that OHM's system is a viable treatment option for PCB-contaminated waste. Also, since PCBs have higher boiling points than VOCs, SVOCs, and PAHs, this treatment option should prove viable for these wastes as well.

The final system for which SITE data is available is Roy F. Weston, Inc.'s heated screw thermal desorber, which is called the LT³® (Low Temperature Thermal Treatment). This unit heats the feedstock to temperatures of 200 to 260 °C in two jacketed troughs, with the vaporized organics being condensed for recycling or further treatment. As with the other technologies, this system can be used to treat PCBs, VOCs, SVOCs, and PAHs, along with fuels, drilling muds, dioxins, furans, pesticides, herbicides, and halogenated and non-halogenated solvents (NTTC, 1997(d)).

Unfortunately, the treatment results for this unit were not as clear as the others presented. During the test runs at the Anderson Development Company Superfund Site

in Adrian, MI, wastes contaminated with VOCs, SVOCs, and 4,4'-methylene bis (2-chloroaniline) (MBOCA) were treated in six tests. The results indicate that MBOCA removal efficiencies of greater than 88 percent were achieved and that VOCs were lowered to below detectable limits. However, dioxins and furans were formed in the system (although they were captured by the off-gas treatment system) and the concentration of phenols increased (NTTC, 1997(d)).

When looking further into the data available on this study, however, it is apparent that the LT³® system is an effective thermal desorption unit. At the Anderson site, the unit achieved the cleanup goals for MBOCA, all VOCs, and seven of eight SVOCs (USEPA, 1995(a)). The production of dioxins and furans is still a concern, but this is mitigated by the fact that they were captured by the off-gas treatment system.

9.2 *Remediation Project Results*

The primary source of data for remediation projects is the USEPA's cost and performance reports for the various projects. Four such reports were available for review, two involving direct-fired rotary kilns and two involving SoilTech's ATP system, which is an indirect-fired rotary kiln. (A fifth report was available covering the LT³® system just reviewed.)

The first cost and performance report was for the McKin Company Superfund site in Gray, ME. Canonie Environmental Services, Corp. utilized their Low Temperature Thermal Aeration (LTTA) system on-site, which is a direct-fired rotary kiln with a soil temperature of 150 °C and a residence time of six minutes (the soil was treated in three passes of two minutes each). This was used to treat 11,000 cubic yards of soil contaminated with halogenated VOCs and PAHs (USEPA, 1995(b)).

During the testing, the EPA established treatment criteria of 0.1 mg/kg for trichloroethylene (TCE), 1 mg/kg for individual PAHs, and 10 mg/kg for total PAHs. The results for the treatment are shown in Table 6. It should be noted that the only contaminant that exceeded its treatment criteria was phenanthrene. However, the high concentrations only occurred during the latter stages of cleanup, and the average phenanthrene level after treatment was 0.92 mg/kg. Due to this, the EPA and Maine's environmental agency both accepted the results as successful treatment (USEPA, 1995(b)).

Table 6. Performance Results for Canonie Environmental Services Corp. (adapted from USEPA, 1995(b)).

CONTAMINANT	RANGE OF TREATED SOIL CONCENTRATIONS ($\frac{\text{mg}}{\text{kg}}$)
VOCs	
1,2-Dichlorobenzene	ND
<i>trans</i> -1,1-Dichlorethane	ND
Tetrachloroethane	ND
1,1,1-Trichloroethane	ND
Trichloroethene	ND to 0.04
PAHs	
Acenaphthene	ND
Anthracene	ND to 0.975
Benzo- <i>a</i> -anthracene	ND to 0.42
Chrysene	ND to 0.495
Fluoranthrene	ND to 0.38
Fluorene	ND
Naphthalene	ND
Phenanthrene	ND to 2.5
Pyrene	ND to 0.76

Clearly, Canonie's system was successful at treating the wastes present at the McKin site. It is not clear why the phenanthrene levels increased at the end of the treatment period, but they were still able to achieve average concentrations that met the treatment criteria established by EPA.

The second direct-fired rotary kiln was utilized at the TH Agriculture & Nutrition Company Superfund site in Albany, GA by Williams Environmental Services, Inc. Their Thermal Desorption Processing Unit #1 (TPU #1) treated soils contaminated with organo-chlorine pesticides at temperature of 450 to 590 °C with a residence time of fifteen minutes. Significantly, stack emissions were also a concern for this system.

During the treatment, EPA established treatment goals for both pesticides and stack emissions. The pesticide treatment goals were a removal percentage greater than 90 percent for BHC-alpha, BHC-beta, 4,4'-DDT, and toxaphene, as well as a total organo-chlorine concentration below 400 mg/kg. The results obtained during the testing are listed in Table 7, while the stack emission results and goals are shown in Table 8.

Table 7. Williams Environmental Treatment Results (adapted from USEPA, 1995(d))

CONTAMINANT	TREATED CONCENTRATION ($\frac{\text{mg}}{\text{kg}}$)	AVERAGE REMOVAL (%)	REMOVAL GOAL (%)
Aldrin	<0.017	>98.64	
BHC-alpha	<0.017	97.84	>90
BHC-beta	<0.017	97.89	>90
BHC-delta	<0.017	>98.28	
Lindane	<0.017	>98.50	
Chlordane-alpha	<0.017	>98.50	
Chlordane-gamma	<0.017	>98.50	
Dieldrin	<0.033	>98.34	
4,4'-DDD	<0.033	>98.50	
4,4'-DDE	2.94	N/A	
4,4'-DDT	<0.017	99.89	>90
Endosulfan	<0.033	>99.65	
Endosulfan II	<0.017	>98.64	
Endrin	<0.033	>98.64	
Toxaphene	<1.70	98.98	>90
Total Pesticides	4.01	N/A	400 $\frac{\text{mg}}{\text{kg}}$

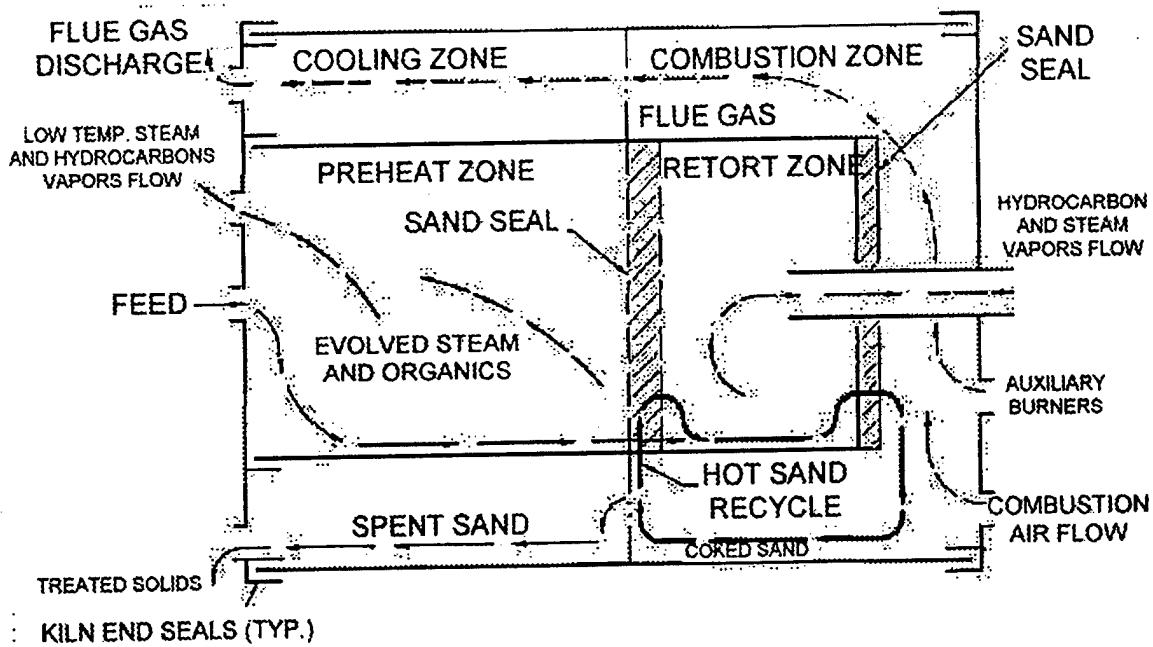
Table 8. Williams Environmental Stack Emissions Results (Adapted from USEPA, 1995(d)).

CONTAMINANT	GOAL	MAXIMUM RECORDED VALUE
Total Hydrocarbons	100 ppmv	35.5 ppmv
HCl	<4 lbs./hr	0.13 lbs./hr
Particulate	<0.08 gr/dscf	0.007 gr/dscf

This unit was exceedingly successful at meeting its remedial goals. The TPU #1 was able to attain all established treatment goals for the waste treated. Also, for those contaminants without treatment standards, the unit still achieved removal efficiencies of greater than 97 percent for each contaminant.

The two cost and performance reports for indirect-fired rotary kilns are both for SoilTech's Anaerobic Thermal Processor (ATP) system. Since this system is somewhat unique, it is helpful to explain its operation prior to discussing its performance. The ATP system (shown schematically in Figure 10) operates in four distinct zones: preheat, retort, combustion, and cooling. In the preheat zone, the soil is heated to 260 °C and the vapors are swept into the preheat vapor cooling system. Next, the soil and remaining contaminants enter the retort zone where they are heated to 510 to 620 °C to remove the more recalcitrant contaminants. In this zone, the thermal cracking of the hydrocarbon contaminants forms a coke that is burned off in the combustion zone. The off-gases from the combustion zone are treated in the combustion zone's off-gas treatment system. Then, the treated soil enters the cooling zone where its heat is recycled back to the preheat and retort zones of the ATP system. A distinctive feature of this system is the spraying of alkaline polyethylene glycol on the waste feed to promote dechlorination in the unit (USEPA, 1995(e)).

Figure 10. SoilTech's ATP Unit (USEPA, 1995(e)).



This system was utilized at both the Pristine, Inc. Superfund site in Reading, OH and the Wide Beach Development Superfund site in Brant, NY. At the Pristine site, the primary contaminants were VOCs, SVOCs, PAHs, pesticides, and inorganic metals, while at the Wide Beach site PCBs were the only contaminant. At the Pristine site, the primary contaminants of concern were 4,4'-DDT, dieldrin, 2,3,7,8-TCDD, benzene, and chloroform (USEPA, 1995(c)). The goals and levels attained for these compounds are shown in Table 9. At Wide Beach, the remediation goal for PCBs was < 2 mg/kg, which was attained for all samples taken (USEPA, 1995(e)).

Table 9. SoilTech Treatment Performance (Adapted from USEPA, 1995(c)).

CONTAMINANT	REMEDIATION LEVEL ($\frac{\mu\text{g}}{\text{kg}}$)	GOAL ($\frac{\mu\text{g}}{\text{kg}}$)
4,4'-DDT	9.9	487
Dieldrin	4.8	6
2,3,7,8-TCDD	0.0123	0.99
Benzene	9	116
Chloroform	9	2043

With the ATP system, SoilTech was able to successfully treat the waste at both sites by meeting the remediation goals set by EPA. The only concern arose at the Wide Beach site where dioxin and furan emissions of 9.52 ng/dscm were noted. However, there were no emission guidelines for these emissions, so the unit was technically in compliance with EPA regulations.

9.3 *Pilot Test Results*

Evaluating thermal blanket technology requires a literature review because these systems do not have cost and performance reports available. One source of information on thermal blankets is Iben's work, which describes the efficiency of thermal blankets for treating PCB-contaminated waste. The thermal blankets, each measuring 2.4m × 6.1m, were used to treat soil at a former auto racetrack where used oil was sprayed to control dust. This offered an ideal location to test the thermal blankets because the contamination depth was shallow.

The blankets studied operate at 815 to 925 °C and heat the soil to 200 °C at a depth of 15 cm. This soil temperature was achieved after 24 hours of heating. Initially, the soil contained PCB levels of 2000 ppm, but after 24 hours of heating, the levels were below 2 ppm. Also, no downward migration of PCBs was observed, thereby eliminating any concern that this treatment might in fact make the contaminants more mobile and increase the hazard (Iben et al., 1996). This represents an impressive removal efficiency of 99.9%, and is indicative of successful treatment. Unfortunately, this technology is limited to treating shallow contamination. It is desirable where applicable, however, because it is an in situ process that does not require any excavation.

10 Cost

Evaluating the cost of thermal desorption requires comparing the costs of the various types of thermal desorption against each other and comparing thermal desorption costs against those of other treatment technologies for soils, sediments, and sludges. While costs will certainly vary depending on site-specific parameters, this will allow a relativistic comparison of implementation cost.

10.1 Costs of Thermal Desorption Technologies

Not surprisingly, there is a wide range in costs for thermal desorption treatment of contaminated wastes. For low temperature thermal desorption, the cost generally ranges from \$40 to \$100 per ton of average soil and \$200 per ton for clay soil. For high temperature thermal desorption, the cost generally ranges from \$100 to \$300 per ton of soil (FRTR, 1997). These ranges are not absolute, as shown in Table 10, because certain vendor's cost estimates are slightly higher or lower. Table 10 also illustrates the different costs for different types of thermal desorption. Notably, rotary kilns with afterburners have the lowest average cost while the SoilTech ATP unit has the highest. The remaining technologies' costs are essentially equal.

Since the various types of thermal desorption are similar in cost, other factors will enter into the decision of which type to use. Things such as vendor availability, startup times, and the waste matrix will all determine which technology is best suited for a particular site.

Table 10. Cost of Individual Thermal Desorption Technologies (compiled from USEPA 1995(b)).

TECHNOLOGY	COST RANGE (\$/ton)	AVERAGE COST (\$/ton) (a)
Rotary Kiln with Afterburner	23 to 400	82
Rotary Kiln with Recovery	60 to 350	176
Rotary Kiln (SoilTech ATP unit)	120 to 400	260
Hollow Screw	50 to 600	185
Thermal Blanket	150 to 200 (b)	175
Infrared Heating	50 to 300	163
Fluidized Bed	Unavailable	Unavailable
(a) Calculated by taking the average of the cost ranges for each vendor.		
(b) Iben et al., 1996		

10.2 Costs of Competing Technologies

It is also beneficial to compare the cost of thermal desorption to other technologies. The results of this effort are presented in Table 11. From these results, it is apparent that low temperature thermal desorption is a very attractive technology from a cost standpoint. High temperature thermal desorption is more expensive, but it is in the middle of the pack with other technologies. It should be noted that these ranges are averages over several applications of the technology and site-specific parameters will determine the cost of a treatment option.

Table 11. Thermal Desorption Cost vs. Competing Technologies (developed from FRTR, 1997)

TECHNOLOGY	COST (\$/ton)	APPLICABILITY	LIMITATIONS
Natural attenuation	N/A	VOCs, SVOCs, fuels	Can only be used when there are no potential receptors
Pneumatic Fracturing	8 to 12	All contaminants in silts, clays, shale, and bedrock	May lead to contaminant migration
Soil Vapor Extraction (SVE) (in situ)	25 to 100 (a)	VOCs, some fuels	Low permeability soils difficult to treat
Low Temperature Thermal Desorption	40 to 100		
Bioventing	25 to 120 (a)	Petroleum hydrocarbons, non-chlorinated solvents, pesticides	High water table and low permeability soils reduce performance
SVE (ex situ)	100	VOCs	Requires substantial space
Solidification-Stabilization (ex situ)	100	Inorganics, limited SVOCs and pesticides	VOCs generally not immobilized
In situ Biodegradation	50 to 200 (a)	Petroleum hydrocarbons, solvents, pesticides, organics	Cleanup goals might not be attained if inadequate contaminant-microorganism contact
Thermally Enhanced SVE	60 to 240 (a)	SVOCs, VOCs	Low permeability soils difficult to treat
Soil Washing	120 to 200	SVOCs, fuels, inorganics, some pesticides and VOCs	Complex waste mixtures difficult to treat
White Rot Fungus	180 (a)	DDT, PAHs, PCBs	Has not been shown to meet cleanup goals
High Temperature Thermal Desorption	100 to 300		
Dehalogenation (base-catalyzed)	245	Halogenated SVOCs and pesticides	High clay and moisture content increase costs
Solvent extraction	100 to 400	PCBs, VOCs, halogenated solvents, petroleum hydrocarbons	Least effective on high molecular weight organics

TECHNOLOGY	COST (\$/ton)	APPLICABILITY	LIMITATIONS
Pyrolysis	300	SVOCs, pesticides	Requires low moisture content feed
Slurry Phase Biological Treatment	300 to 390 (a)	Petroleum hydrocarbons, petrochemicals, solvents, pesticides, organics	Sizing of materials difficult and expensive
Solidification-Stabilization (in situ)	100 to 150 (a) (shallow) 360 to 600 (a) (deep)	Inorganics, limited application with SVOCs	Depth of contaminant may limit application
Controlled Solid Phase Biological Treatment	240 to 480 (a)	VOCs; fuels; halogenated VOCs, SVOCs, and pesticides	Requires substantial space
Landfarming	240 to 480 (a)	Petroleum hydrocarbons	Requires substantial space
Excavation, retrieval, and off-site disposal	270 to 460	All contaminants	Generation of fugitive dusts are exposure hazard
Vitrification (ex situ)	700	Inorganics	Organic off-gases require treatment
Incineration	1,500 to 6,000	Chlorinated hydrocarbons, PCBs, dioxins	Volatile heavy metals require special off-gas treatment

(a) Calculated by assuming a soil bulk density of 1400 kg/m³

11 Worker Safety Evaluation

When performing remedial operations under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA), the risk of the project must be evaluated. This typically involves performing a risk assessment, the legal requirements for which are contained in 40 CFR § 300.430. In the risk assessment, the lead agency is to characterize the "nature of and threat posed by the hazardous substances and hazardous materials" present at the site, and is to use this data to conduct a site-specific risk assessment (40 CFR § 300.430). The risk assessment should characterize both the

current and potential threats to human health through contaminants "migrating to ground water or surface water, releasing to air, leaching through soil, remaining in the soil, and bioaccumulating in the food chain." (40 CFR § 300.430).

When talking of *risks*, the EPA defines both short and long-term risks, each of which must be evaluated during the risk assessment. EPA guidance states that short-term risks are those "that occur during implementation of a remedial alternative," while long-term risks are those "that remain after remedy implementation is complete." (USEPA, 1991). When evaluating long-term, human health risks, EPA guidance instructs the assessor to:

- (1) Evaluate the residual risk
- (2) Evaluate the protectiveness over time

In contrast, the short-term risk assessment should:

- (1) Evaluate the short-term exposure
- (2) Characterize the short-term risks to the communities
- (3) Characterize the short-term risks to the workers (USEPA, 1991).

In effect, the long-term risk assessment is performed when the performance of the remedial option is evaluated (Section 9), so it will not be repeated here. The short-term risk assessment, however, involves determining the worker exposures resulting from remedial activities. For thermal desorption, worker exposures fall into three categories: normal industrial exposures (rotating machinery, heavy equipment, etc.); stack emissions; and fugitive emissions. Since the stack emissions and fugitive emissions are peculiar to remedial efforts they will be discussed further.

(Another possible exposure concern is direct exposure to contaminants in systems with contaminant recovery. The specific exposures from these systems will depend heavily on the specific system and the training and work practices of the workers. Since detailed information on these factors is not available, these exposures will not be discussed.)

11.1 Stack Emissions

Stack emissions are a potentially dangerous source of airborne contaminants at Superfund sites. In order to evaluate worker exposures due to stack emissions, it is helpful to look at actual emissions data from some Superfund sites. Table 12 shows data from three Superfund sites where thermal desorption was utilized: SoilTech's ATP unit was used at Pristine, Inc. and Wide Beach; and Williams Environmental Service's TDU#1 was used at TH Agriculture.

From the data in Table 12, one can see that the stack emissions were below regulatory limits at each site. However, it is also useful to estimate airborne concentrations based on the recorded stack emissions from each thermal desorption unit. The simplest way to accomplish this is to calculate the stack exit concentrations for each contaminant based on the stack gas flow rate and the contaminant flow rate for those contaminants that were not originally measured in concentration units (see Appendix C for conversion equations).

Table 12. Stack Emissions for Thermal Desorption Applications (USEPA 1995(c through e)).

PRISTINE, INC.		
CONTAMINANT	EMISSIONS	LIMIT
Particulate (gr/dscf)	<0.00078	0.015
Total Dioxin and Furan (ng/dscm)	0.013	<30
HCl (lbs./hr)	0.00851 to 0.0144	<4
Total Hydrocarbons (ppm)	5.6 to 8.8	<20
SO ₂ (gm/sec)	<1	16.6

WIDE BEACH		
CONTAMINANT	EMISSIONS	LIMIT
Particulate (gr/dscf)	0.04	0.05
Total Dioxin and Furan (ng/dscm)	9.54	NONE
PCBs (lbs./hr)	1.0×10^{-5}	3.33×10^{-5}
Polyethylene Glycol (lbs./hr)	4.0×10^{-5}	4.16×10^{-5}

TH AGRICULTURE		
CONTAMINANT	EMISSIONS	LIMIT
Particulate (gr/dscf)	0.0006	<0.08
Toxaphene ($\mu\text{g}/\text{m}^3$)	0.045	1.48
HCl (lbs./hr)	0.12	<4
Total Hydrocarbons (ppm)	11.9	100
4,4'-DDT ($\mu\text{g}/\text{m}^3$)	ND	2.96

Table 13. Estimated Contaminant Concentrations at Stack Exhaust.

PRISTINE, INC.			
CONTAMINANT	STACK CONCENTRATION	ACGIH TLV	OSHA PEL
Particulate (mg/m ³)	1.05	3	15
Total Dioxin and Furan (mg/m ³)	7.6×10 ⁻⁹	NONE	NONE
HCl (ppm)	0.7	5	5
Total Hydrocarbons (ppm)	8.8	NONE	NONE
SO ₂ (mg/m ³)	<258	5.2	13
WIDE BEACH			
CONTAMINANT	STACK CONCENTRATION	ACGIH TLV	OSHA PEL
Particulate (mg/m ³)	53.8	3	15
Total Dioxin and Furan (mg/m ³)	5.6×10 ⁻⁶	NONE	NONE
PCBs (mg/m ³)	3.0×10 ⁻⁴	0.5	0.5
Polyethylene Glycol (ppm)	1.2×10 ⁻³	NONE	NONE
TH AGRICULTURE			
CONTAMINANT	STACK CONCENTRATION	ACGIH TLV	OSHA PEL
Particulate (mg/m ³)	0.8	3	15
Toxaphene (mg/m ³)	4.5×10 ⁻⁵	0.5	0.5
HCl (ppm)	2.1	5	5
Total Hydrocarbons (ppm)	11.9	NONE	NONE
4,4'-DDT (mg/m ³)	ND	1	1

The last two columns in Table 13 contain the American Conference of Governmental Industrial Hygienists (ACGIH) Threshold Limit Values (TLVs®) and the Occupational Safety and Health Administration (OSHA) Permissible Exposure Limits (PELs) for the various contaminants (ACGIH, 1996; 29 CFR § 1910.1000). These values represent guidelines for acceptable workplace exposures to hazardous compounds, and, since the TLVs are more conservative, the airborne concentrations and the TLVs will be compared. In Table 13, the contaminant concentration at the stack exceeds the TLV on two occasions: SO₂ at Pristine, Inc. and particulate at Wide Beach.

In order to determine if these emissions pose a hazard to on-site workers, the concentration of the contaminants in the workers' breathing zones must be estimated. (It is certainly unlikely that anyone will inhale the stack exhaust for eight hours a day.) This is best done by using an air dispersion model to estimate the ambient contaminant concentration at a given distance from the stack. For this data, the US Air Force's Toxic Chemical Dispersion Model V. 4.1 (USAF, 1992) was used to determine the maximum ambient concentration for each contaminant based on the following assumptions:

- (1) Ambient temperature of 25°C,
- (2) Wind speed of 5 m/s,
- (3) Dry ground,
- (4) Clear skies,
- (5) No inversion layers,
- (6) Stack height of 5 m, and a
- (7) Worker height of 2 m.

With these assumptions, the model generated the following data:

Table 14. Air Quality Model Estimates of Contaminant Concentrations.

CONTAMINANT	MAX. CONCENTRATION (mg/m ³)	LOCATION (m downwind)
SO ₂	<16.76	250
Particulate	1.3×10^{-2}	270

These model results indicate that SO₂ may exceed its TLV under the model assumptions. However, based on the accuracy of the emission presented, this cannot be stated for certain. It does indicate, however, that even if all the emission standards were met at the sites, the applicable TLV values could still be exceeded. This serves to

illustrate that it is not acceptable to only meet the regulatory requirements for stack emissions, but modeling must be done to estimate concentrations in the workers' breathing zones. This will help to ensure that on-site personnel do not exceed any TLVs.

11.2 Fugitive Emissions

Since most thermal desorption systems are ex situ processes, they require soil excavation prior to treatment. When disturbing contaminated soil with heavy machinery, fugitive contaminant emissions are a concern. Specifically, the primary concerns arise due to emissions from:

- (1) Exposed waste in an excavation pit,
- (2) Material as it is dumped from the excavation bucket, and
- (3) Waste/soil in short-term storage piles (USEPA, 1992).

The magnitude of the emissions will depend on several site-specific parameters, including the contaminants and soil characteristics.

The EPA developed equations to calculate the emission rates for both long-term and short-term exposures based on site-specific data. The results of these equations can then be used to estimate ambient contaminant concentrations based on graphs contained in USEPA, 1992. The equations required for these calculations are contained in Appendix C, along with definitions of the various factors.

Unfortunately, performing these calculations accurately requires detailed site information, which is not readily available, so the estimated concentrations for the various contaminants were not calculated. Fugitive emissions are an exposure concern, however, and they must be evaluated to determine the appropriate methods to control them.

12 Thermal Desorption as a Treatment Option

While considering thermal desorption as a treatment option, several factors must be evaluated, including efficiency, cost, and safety. From the discussion above, one can see that thermal desorption is an attractive treatment option, but it is not the only option available. There are dozens of technologies available to treat contaminated sites, but the one most suitable for comparison with thermal desorption is incineration because they are similar technologies.

Thermal desorption has several advantages over incineration, with greater public acceptance chief among them. There are also many technical advantages, however. When compared with incineration, thermal desorption creates a significantly smaller volume of off-gases; solids entrainment in the off-gas is minimized; and organic contaminants can be recovered for recycling (Wilson et al., 1994). Of equal importance is the fact that thermal desorption units generally do not produce dioxins and furans (PICs) as incinerators do (although direct-fired thermal desorption units may create these compounds) (Page, 1997).

These advantages have not gone unnoticed by industry and the EPA as thermal desorption is becoming one of the preferred methods of cleaning soil contaminated with volatile compounds (O'Brien et al., 1995). Also, the EPA has acknowledged thermal desorption under its Superfund Accelerated Cleanup Model (SACM). This program attempts to expedite the investigative and remedial portions of the cleanup process by naming Presumptive Remedies. (A Presumptive Remedy is the default cleanup option for a particular type of contaminated site.) Notably, thermal desorption, along with soil vapor extraction and incineration, are Presumptive Remedies for VOC-contaminated

sites. However, soil vapor extraction is the primary presumptive remedy for these sites (Artrip, 1996).

With this blessing from the EPA, thermal desorption has been utilized more frequently in recent years. As Figure 11 shows, thermal desorption was used at 51 Superfund sites, or seven percent of all Superfund sites through fiscal year 1994. Also, Figure 12 illustrates that thermal desorption, while not an everyday technology, is slowly increasing in popularity. This is evidenced further by thermal desorption's standing among other innovative technologies. For data through August 1995, there were 297 innovative technology projects completed or underway, and thermal desorption accounted for 51 or 17 percent of them (Fielder et al., 1996).

Figure 11. Superfund Remedial Actions (Fielder et al., 1996)

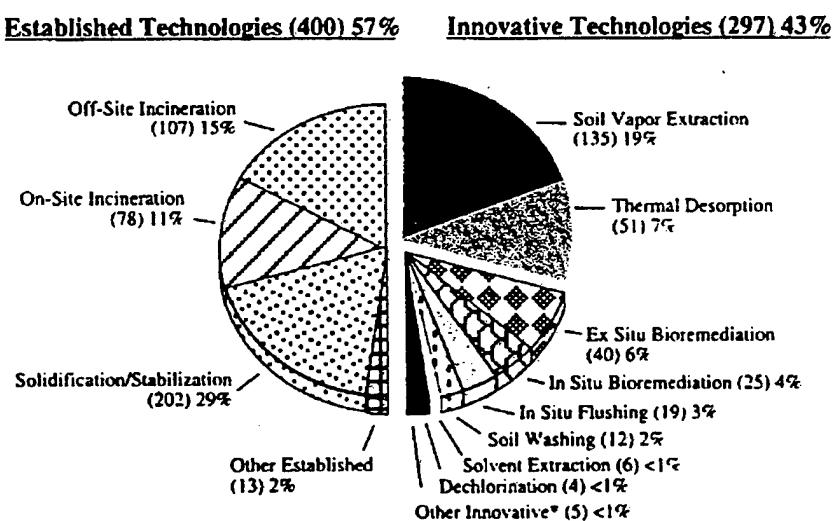
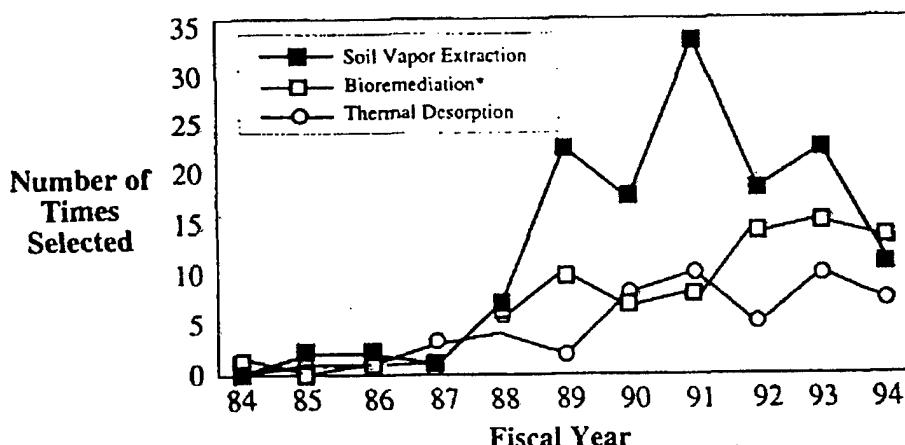


Figure 12. Superfund Remedial Action Trends (Fielder et al., 1996)



These numbers certainly bode well for thermal desorption and the many contractors involved with the technology. Currently, thirty-seven vendors are listed in the EPA's VISITT database (Vendor Information System for Innovative Treatment Technologies), and this number is sure to rise as it becomes a more common technology. Also, there are many opportunities for additional innovation such as infrared furnaces and thermal blankets. Likely, the number of thermal desorption systems available will increase as companies develop special systems for niche applications (as thermal blankets are only applicable to shallow contamination).

13 Conclusions

Thermal desorption has become an attractive treatment option because of its ability to compete favorably with other technologies to remediate soils, sludges, and sediments. Significantly, thermal desorption can treat a wide range of volatile compounds, and is the preferred method of treating PCB waste because PICs are

generally not formed (Page, 1997). Also, thermal desorption is able to treat these wastes at comparable, and in many cases much lower, costs to other treatment options.

The advantages of thermal desorption include its ability to recover contaminants for recycling and its greater public acceptance than incineration. When recovering contaminants for recycling, companies are able to lower their hazardous waste disposal costs and defray the cost of thermal desorption by using the recycled material in their processes. When comparing thermal desorption to incineration, it has the advantage of generating lower volumes of off-gas and entraining less particulate in the off-gas.

Thermal desorption is not without potential hazards, however. As with any treatment option, it requires on-site personnel to work with hazardous materials, many times in situations that are difficult to control. When excavating large volumes of contaminated soils, the potential for ambient concentrations of hazardous compounds to exceed ACGIH TLV values is real and must be evaluated on a case-by-case basis. Another possible hazard exists from stack gases that contain contaminants. An analysis of three sites where thermal desorption was used indicated that only SO₂ exceeded its TLV value, so this exposure route must also be evaluated. When considering the entire site, all known hazards must be evaluated by safety professionals to obtain an estimate of the hazards associated with the remedial project. These estimates should be combined with continuing on-site measurements of airborne contaminant concentrations to refine the estimates. This process will allow the on-site safety professionals to periodically modify safety controls over the life of the project as more information becomes available.

Despite these concerns, which exist whenever remediation occurs, thermal desorption is a viable method of treating soils, sediments, and sludges contaminated with

VOCs, SVOCs, PAHs, PCBs, and other volatile compounds. Since these contaminants are present at numerous sites throughout the country, thermal desorption will certainly be used more and more frequently as a remediation tool.

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APPENDIX

A

Appendix A: List of Acronyms

-A-

ACGIH: American Conference of Governmental Industrial Hygienists

ATP: Anaerobic Thermal Processor

-B-

BHC: Benzene Hexachloride (Lindane)

-C-

CDD: Chlorodibenzo-*p*-dioxin

CDF: Chlorodibenzofuran

CERCLA: Comprehensive Environmental Response, Compensation, and Liability Act

CFR: Code of Federal Regulations

-D-

DDT: Dichlorodiphenyltrichloroethane

DMSO: Dimethyl Sulfoxide

DRE: Destruction and Removal Efficiency

-E-

EPA: Environmental Protection Agency

-F-

FRTR: Federal Remediation Technologies Roundtable

-I-

ITT: Innovative Treatment Technologies

-L-

LTTA: Low Temperature Thermal Aeration

LT³: Low Temperature Thermal Treatment

-M-

MBOCA: 4,4'-Methylene bis (2-chloroaniline)

-N-

NTTC: National Technology Transfer Center

-O-

OSHA: Occupational Safety and Health Administration

-P-

PAH: Polycyclic Aromatic Hydrocarbon
PCB: Polychlorinated Biphenyl
PEL: Permissible Exposure Limit
PIC: Products of Incomplete Combustion
POHC: Principle Organic Hazardous Constituent

-R-

RCRA: Resource Conservation and Recovery Act

-S-

SACM: Superfund Accelerated Cleanup Model
SITE: Superfund Innovative Technology Evaluation
SVE: Soil Vapor Extraction
SVOC: Semi-volatile Organic Compound

-T-

TCDD: Tetrachlorodibenzo-*p*-dioxin
TCE: Trichloroethylene
TDU: Thermal Desorption Unit
TLV: Threshold Limit Value
TPU#1: Thermal Processing Unit #1

-U-

USC: United States Code

-V-

VISITT: Vendor Information System for Innovative Treatment Technologies
VOC: Volatile Organic Compound

APPENDIX

B

Appendix B. Thermal Desorption Contractors (USEPA, 1996(b)).

Vendor Name: ADVANCED ENVIRONMENTAL SERVICES, INC.
Technology Type: ROTARY KILN (DIRECT-FIRED) WITH AFTERBURNER

Technology Trade Name:

Address: Corporate Centre 200, Box 160
200 35th Street
City: Marion, Iowa 52302-0160
USA
Contact: Tad Cooper
Title: Business Director
Phone: (800) 289-7371
Fax: (319) 377-0075
e-mail: Not Provided
Web Page: Not Provided
Status: Full scale

ESTIMATED PRICE RANGE
Estimated price range per unit of waste treated:
\$ 50 to \$ 125 per ton

Vendor Name: ARIEL INDUSTRIES, INC.
Technology Type: ROTARY KILN WITH AFTERBURNER

Technology Trade Name: Ariel SST Low Temperature Thermal Desorber

Address: 2204 Industrial South Road
City: Dalton, Georgia 30721
USA
Contact: Timothy L. Boyd
Title:
Phone: (706) 277-7070
Fax: (706) 277-7945
e-mail: Not Provided
Web Page: Not Provided
Status: Full scale

ESTIMATED PRICE RANGE
Estimated price range per unit of waste treated :
\$ 65.00 to \$ 200.00 per ton

Vendor Name: CARLO ENVIRONMENTAL TECHNOLOGIES, INC.
Technology Type: ROTARY KILN WITH AFTERBURNER

Technology Trade Name:

Address: 44907 Trinity Drive
P.O. Box 744
City: Clinton Township, Michigan 48038-0744
USA
Contact: Keith Flemingloss
Title: Manager of Environmental Services
Phone: (810) 468-9580
Fax: (810) 468-9589
e-mail: Not Provided
Web Page: Not Provided
Status: Full scale

ESTIMATED PRICE RANGE
Estimated price range per unit of waste treated :
\$ 30 to \$ 60 per ton

Vendor Name: CARSON ENVIRONMENTAL
Technology Type: PADDLE AUGERS (INDIRECT-FIRED) WITH UV
DESTRUCTION

Technology Trade Name:

Address: 11734 Gateway Boulevard
City: Los Angeles, California 90064
USA
Contact: R.Carson Later
Title: President
Phone: (310) 478-0792
Fax: (310) 479-8898
e-mail: Not Provided
Web Page: Not Provided
Status: Pilot scale

ESTIMATED PRICE RANGE
Estimated price range per unit of waste treated :
\$ _____ to \$ _____ per _____

Vendor Name: CASWAN ENVIRONMENTAL SERVICES LTD.
Technology Type: ROTARY KILN (INDIRECT-FIRED) WITH RECOVERY

Technology Trade Name: Thermal Distillation And Recovery (TDR)

Address: Bay 1, 2916 5th Avenue, N.E.

City: Calgary, Alberta T2A 6K9
Canada

Contact: R. Welke
Title: Manager, Business Development
Phone: (403) 235-9333
Fax: (403) 248-9600
e-mail: Not Provided
Web Page: Not Provided
Status: Full scale

ESTIMATED PRICE RANGE

Estimated price range per unit of waste treated :
\$ 75.00 to \$ 300 per ton

Vendor Name: CLEAN-UP TECHNOLOGY, INC.
Technology Type: ROTARY KILN WITH AFTERBURNER

Technology Trade Name:

Address: 145 West Walnut Street

City: Gardena, California 90248
USA

Contact: Ron Morris
Title: National Sales Manager
Phone: (310) 327-8605
Fax: (310) 327-8616
e-mail: Not Provided
Web Page: Not Provided
Status: Full scale

ESTIMATED PRICE RANGE

Estimated price range per unit of waste treated :
\$ 20.00 to \$ 100.00 per ton

Vendor Name: CONTECK ENVIRONMENTAL SERVICES, INC.
Technology Type: ROTARY KILN WITH AFTERBURNER

Technology Trade Name: Soil Roaster

Address: 22460 Highway 169 Northwest

City: Elk River, Minnesota 55330-9235
USA

Contact: Chris Kreger
Title: President
Phone: (612) 441-4965
Fax: (612) 441-2025
e-mail: Not Provided
Web Page: Not Provided
Status: Full scale

ESTIMATED PRICE RANGE

Estimated price range per unit of waste treated :
\$ 22.00 to \$ 65.00 per ton

Vendor Name: COVENANT ENVIRONMENTAL TECHNOLOGIES, INC.
Technology Type: STATIONARY KILN WITH RECOVERY

Technology Trade Name: Mobile Retort Unit

Address: 45 South Idlewild
Suite 107
City: Memphis, Tennessee 38104
USA
Contact: Valerie Humpherys
Title: Controller
Phone: (901) 278-2134
Fax: (901) 278-2134
e-mail: Not Provided
Web Page: Not Provided
Status: Full scale

ESTIMATED PRICE RANGE

Estimated price range per unit of waste treated :
\$ 100 to \$ 800 per ton

Vendor Name: DURATHERM, INC.
Technology Type: ROTARY KILN (INDIRECT-FIRED) WITH RECOVERY

Technology Trade Name: Duratherm Desorption (TM)

Address: P.O. Box 58466

City: Houston, Texas 77258
USA

Contact: Brad Hogan
Title: Vice president
Phone: (713) 339-1352
Fax: (713) 559-1364
e-mail: Not Provided
Web Page: Not Provided
Status: Full scale

ESTIMATED PRICE RANGE

Estimated price range per unit of waste treated :
\$ 100 to \$ 350 per ton

Vendor Name: ECOTECHNIEK B.V.
Technology Type: ROTARY KILN

Technology Trade Name: Etts Ecotechniek Thermal Treatment System

Address: Het Kwadrant 1

City: Maarssen, 3606 AZ
The Netherlands

Contact: J. Bouman
Title: Engineer
Phone: (346) 557-700
Fax: (346) 554-452
e-mail: Not Provided
Web Page: Not Provided
Status: Full scale

ESTIMATED PRICE RANGE

Estimated price range per unit of waste treated:
\$ 60 to \$ 200 per metric ton

Vendor Name: ENVIRO-KLEAN SOILS, INC.
Technology Type: DIRECT-FIRED REACTOR WITH AFTERBURNER

Technology Trade Name: The Klean Machine

Address: P.O. Box 2003
City: Snoqualmie, Washington 98065
USA
Contact: R.T. Cokewell
Title: President
Phone: (206) 888-9388
Fax: (206) 888-9688
e-mail: cokewell@aol.com
Web Page: Not Provided
Status: Full scale

ESTIMATED PRICE RANGE
Estimated price range per unit of waste treated :
\$ 55.00 to \$ 100.00 per ton

Vendor Name: HAZEN RESEARCH, INC.
Technology Type: ROTARY KILN WITH AFTERBURNER

Technology Trade Name:

Address: 4601 Indiana Street
City: Golden, Colorado 80403
USA
Contact: Charles W. (Rick) Kenney
Title: Executive Vice President
Phone: (303) 279-4501
Fax: (303) 278-1528
e-mail: Not Provided
Web Page: Not Provided
Status: Pilot scale

ESTIMATED PRICE RANGE
Estimated price range per unit of waste treated :
\$ _____ to \$ _____ per _____

Vendor Name: IT CORPORATION
Technology Type: ROTARY KILN (INDIRECT-FIRED)

Technology Trade Name:

Address: 312 Directors Drive
City: Knoxville, Tennessee 37923
USA
Contact: Edward Alperin/Stuart Shealy
Title: Treatability Mgr./Engineering Sec. Mgr
Phone: (423) 690-3211
Fax: (423) 694-9573
e-mail: Not Provided
Web Page: Not Provided
Status: Pilot scale

ESTIMATED PRICE RANGE

Estimated price range per unit of waste treated :

\$ _____ to \$ _____ per _____

Vendor Name: KALKASKA CONSTRUCTION SERVICE, INC.
Technology Type: ROTARY KILN WITH AFTERBURNER

Technology Trade Name:

Address: 500 South Maple
P.O. Box 427
City: Kalkaska, Michigan 49646
USA
Contact: David Hogerheide/Justin Straksis
Title: Vice President/Superintendent
Phone: (616) 258-9134
Fax: (616) 258-6113
e-mail: Not Provided
Web Page: Not Provided
Status: Full scale

ESTIMATED PRICE RANGE

Estimated price range per unit of waste treated :

\$ 35.00 to \$ 60.00 per ton

Vendor Name: MAXY MILLIAN TECHNOLOGIES, INC.
Technology Type: ROTARY KILN

Technology Trade Name:

Address: 1801 East Street
City: Pittsfield, Massachusetts 01201
USA
Contact: Neal Maxymillian
Title: Vice President
Phone: (617) 557-6077
Fax: (617) 557-6088
E-mail: nmaxymillian@maxymillian.com
Web Page: Not Provided
Status: Full scale

ESTIMATED PRICE RANGE

Estimated price range per unit of waste treated:
\$ 40 to \$ 300 per ton

Vendor Name: MAXY MILLIAN TECHNOLOGIES, INC.
Technology Type: ROTARY KILN (INDIRECT-FIRED) WITH RECOVERY

Technology Trade Name: Indirect System

Address: 1801 East Street
City: Pittsfield, Massachusetts 01201
USA
Contact: Neal Maxymillian
Title: Vice President
Phone: (617) 557-6077
Fax: (617) 557-6088
e-mail: nmaxymillian@maxymillian.com
Web Page: Not Provided
Status: Full scale

ESTIMATED PRICE RANGE

Estimated price range per unit of waste treated :
\$ 70 to \$ 150 per ton

Vendor Name: MCLAREN/HART ENVIRONMENTAL ENGINEERING
Technology Type: INFRARED HEATER

Technology Trade Name: IRV-100 Hydrocarbon Extraction Systems

Address: 9323 Stockport Place
City: Charlotte, North Carolina 28273
USA
Contact: Jeff O'Ham/Cary Lester
Title: Technical Director/Project Manager
Phone: (704) 587-0003
Fax: (704) 587-0693
e-mail: jeff_oham@mclaren-hart.com
Web Page: www.mclaren-hart.com
Status: Full scale

ESTIMATED PRICE RANGE

Estimated price range per unit of waste treated :
\$ 50 to \$ 150 per ton

Vendor Name: MCLAREN/HART ENVIRONMENTAL ENGINEERING
Technology Type: INFRARED HEATER

Technology Trade Name: IRHV-200 High Vacuum Low Temp. Thermal Desorption

Address: 9323 Stockport Place
City: Charlotte, North Carolina 28273
USA
Contact: Jeff O'Ham/Cary Lester
Title: Technical Director/Project Manager
Phone: (704) 587-0003
Fax: (704) 587-0693
e-mail: jeff_oham@mclaren-hart.com
Web Page: www.mclaren-hart.com
Status: Full scale

ESTIMATED PRICE RANGE

Estimated price range per unit of waste treated :
\$ 50 to \$ 150 per ton

Vendor Name: MIDWEST SOIL REMEDIATION, INC.
Technology Type: THERMAL DESORPTION

Technology Trade Name: Mobile Low Temperature Thermal Desorption

Address: 1480 Sheldon Drive

City: Elgin, Illinois 60120
USA

Contact: Bruce Penn
Title: General Manager
Phone: (847) 742-4331
Fax: (847) 742-4294
e-mail: Not Provided
Web Page: Not Provided
Status: Full scale

ESTIMATED PRICE RANGE

Estimated price range per unit of waste treated :
\$ 30.00 to \$ 150.00 per ton

Vendor Name: PET-CON SOIL REMEDIATION, INC.
Technology Type: ROTARY KILN (INDIRECT-FIRED) WITH AFTERBURNER

Technology Trade Name:

Address: P.O. Box 205

City: Spring Green, Wisconsin 53588
USA

Contact: Tom Labudde
Title: General Manager
Phone: (608) 588-7365
Fax: (608) 588-7606
e-mail: Not Provided
Web Page: Not Provided
Status: Full scale

ESTIMATED PRICE RANGE

Estimated price range per unit of waste treated :
\$ 27 to \$ 45 per ton

Vendor Name: PHILIP ENVIRONMENTAL SERVICES CORP.
Technology Type: INDIRECT-FIRED WITH RECOVERY

Technology Trade Name:

Address: 10 Duff Road
Suite 500
City: Pittsburgh, Pennsylvania 15235
USA
Contact: Teresa Sabol Spezio
Title: Senior Engineer
Phone: (412) 244-9000
Fax: (412) 244-9100
e-mail: Not Provided
Web Page: Not Provided
Status: Full scale

ESTIMATED PRICE RANGE

Estimated price range per unit of waste treated :
\$ 200 to \$ 1000 per ton

Vendor Name: PURGO, INC.
Technology Type: ROTARY KILN (INDIRECT-FIRED) WITH RECOVERY

Technology Trade Name: Indirect Heated Portable Unit

Address: 11023 Washington Highway
Suite 100
City: Glen Allen, Virginia 23059
USA
Contact: David Holcomb/Coleman King/Bill Grove
Title: Sales Exec./Spec. Projects Manager/VP
Phone: (804) 550-0400
Fax: (804) 550-3833
e-mail: purgoinc@aol.com(purgoinc)
Web Page: Not Provided
Status: Full scale

ESTIMATED PRICE RANGE

Estimated price range per unit of waste treated :
\$ 60 to \$ 300 per ton

Vendor Name: REMEDIATION TECHNOLOGIES, INC.
Technology Type: HOLLOW SCREW WITH RECOVERY

Technology Trade Name: Thermatek

Address: 9 Pond Lane
Damonmill Square
City: Concord, Massachusetts 01742
USA
Contact: Mark McCabe
Title: Scientist
Phone: (508) 371-1422
Fax: (508) 369-9279
e-mail: Not Provided
Web Page: Not Provided
Status: Full scale

ESTIMATED PRICE RANGE
Estimated price range per unit of waste treated :
\$ 100.00 to \$ 600.00 per ton

Vendor Name: REMTECH, INC.
Technology Type: ROTARY KILN WITH AFTERBURNER

Technology Trade Name:

Address: 9109 West Electric Avenue
City: Spokane, Washington 99204-9035
USA
Contact: Keith G. Carpenter/William R. Bloom
Title: President/Operations Manager
Phone: (509) 624-0210
Fax: (509) 624-6763
e-mail: Not Provided
Web Page: Not Provided
Status: Full scale

ESTIMATED PRICE RANGE
Estimated price range per unit of waste treated :
\$ 40 to \$ 125 per ton

Vendor Name: ROY F. WESTON, INC.

Technology Type: HOLLOW SCREW (INDIRECT-FIRED) WITH RECOVERY

Technology Trade Name: Low Temperature Thermal Treatment (LT3)

Address: 1 Weston Way

City: West Chester, Pennsylvania 19380
USA

Contact: Michael G. Cosmos, P.E./Al Murphy

Title: Treatment Systems Department Manager

Phone: (610) 701-7423

Fax: (610) 701-5035

e-mail: cosmosm@wcpostz.rfweston.com

Web Page: www.rfweston.com

Status: Full scale

ESTIMATED PRICE RANGE

Estimated price range per unit of waste treated :

\$ 60.00 to \$ 150.00 per ton

Vendor Name: RUST INTERNATIONAL, INC.

Technology Type: ROTARY KILN (INDIRECT-FIRED) WITH RECOVERY

Technology Trade Name: X*TRAX (TM)

Address: Clemson Technology Center
100 Technology Drive

City: Anderson, South Carolina 29625
USA

Contact: Carl Palmer

Title: Project Manager

Phone: (864) 646-2413

Fax: (864) 646-5311

e-mail: Not Provided

Web Page: Not Provided

Status: Full scale

ESTIMATED PRICE RANGE

Estimated price range per unit of waste treated :

\$ 125 to \$ 225 per ton

Vendor Name: SEPARATION AND RECOVERY SYSTEMS, INC.
Technology Type: HOLLOW SCREW WITH RECOVERY

Technology Trade Name: SAREX MX-1500, MX-2000/2500/3000 Thermal Processor

Address: 1762 McGaw Avenue

City: Irvine, California 92714-4962
USA

Contact: William J. Sheehan
Title: Senior Vice President
Phone: (714) 261-8860
Fax: (714) 261-6010
e-mail: Not Provided
Web Page: Not Provided
Status: Full scale

ESTIMATED PRICE RANGE
Estimated price range per unit of waste treated :
\$ 50.00 to \$ 150.00 per ton

Vendor Name: SMITH ENVIRONMENTAL TECHNOLOGIES CORP.
Technology Type: ROTARY KILN (DIRECT-FIRED) WITH AFTERBURNER

Technology Trade Name: Low Temperature Thermal Aeration (LTTA)

Address: 304 Inverness Way South
Suite 200

City: Englewood, Colorado 80246
USA

Contact: Joseph H. Hutton
Title: Regional Manager
Phone: (303) 790-1747
Fax: (303) 790-0186
e-mail: Not Provided
Web Page: Not Provided
Status: Full scale

ESTIMATED PRICE RANGE
Estimated price range per unit of waste treated :
\$ 60 to \$ 150 per ton

Vendor Name: SOIL REMEDIATION OF PHILADELPHIA, INC.
Technology Type: ROTARY KILN WITH AFTERBURNER

Technology Trade Name:

Address: 3201 South 61st Street
City: Philadelphia, Pennsylvania 19153
USA
Contact: Matthew Paolino
Title: General Manager
Phone: (215) 724-5520
Fax: (215) 724-2939
e-mail: Not Provided
Web Page: Not Provided
Status: Full scale

ESTIMATED PRICE RANGE

Estimated price range per unit of waste treated :
\$ 45 to \$ 50 per ton

Vendor Name: SOIL SOLUTIONS, INC.
Technology Type: STEAM STRIPPING

Technology Trade Name: CleanSoil Process

Address: 1703 Vargrave Street
City: Winston-Salem, North Carolina 27107
USA
Contact: Jon Ransom
Title: Business Manager
Phone: (910) 725-5844
Fax: (910) 725-6244
e-mail: jcransom@aol.com
Web Page: Not Provided
Status: Full scale

ESTIMATED PRICE RANGE

Estimated price range per unit of waste treated :
\$ _____ to \$ _____ per _____

Vendor Name: SOILTECH ATP SYSTEMS, INC.
Technology Type: ROTARY KILN (INDIRECT-FIRED) WITH RECOVERY

Technology Trade Name: SoilTech ATP System

Address: 304 Inverness Way South
City: Englewood, Colorado 80112
USA
Contact: Joe Hutton
Title: President
Phone: (303) 790-1747
Fax: (303) 799-0186
e-mail: Not Provided
Web Page: Not Provided
Status: Full scale

ESTIMATED PRICE RANGE

Estimated price range per unit of waste treated :
\$ 120.00 to \$ 400.00 per ton

Vendor Name: SOMEUS & PARTNERS UNLIMITED
Technology Type: ROTARY KILN (DIRECT- AND INDIRECT-FIRED) WITH
AFTERTURNER

Technology Trade Name: PCS Low Temperature Thermal Desorption

Address: United Nations APCTT Intl. Tech. Transfer Branch
Bmawan Office, New Memrauli Road, P.O. Box 4575
City: New Delhi, 110016
India
Contact: G. Edward Someus/Dr. Vadim Kotelnikov
Title: Inventor
Phone: 91-11-685-6276
Fax: 91-11-685-6274
e-mail: Cable: APICETITI
Web Page: Telex: 31-73271 APCT IN
Status: Full scale

ESTIMATED PRICE RANGE

Estimated price range per unit of waste treated :
\$ 100 to \$ 400 per cubic meter

Vendor Name: SOUTHWEST SOIL REMEDIATION, INC.
Technology Type: ROTARY KILN WITH AFTERBURNER

Technology Trade Name:

Address: 3951 East Columbia Street
City: Tucson, Arizona 85714
USA
Contact: Trevor Johansen
Title: President
Phone: (602) 571-7174
Fax: (602) 571-7730
e-mail: Not Provided
Web Page: Not Provided
Status: Full scale

ESTIMATED PRICE RANGE

Estimated price range per unit of waste treated :
\$ 40.00 to \$ 250.00 per ton

Vendor Name: SPI/ASTEC
Technology Type: ROTARY KILN WITH AFTERBURNER

Technology Trade Name: LTTD with Heat Recovery

Address: P.O. Box 72787
4101 Gerome Avenue
City: Chattanooga, Tennessee 37407
USA
Contact: Wendell R. Feltman, P.E.
Title: Vice President
Phone: (423) 867-4210
Fax: (423) 827-1550
e-mail: Not Provided
Web Page: Not Provided
Status: Full scale

ESTIMATED PRICE RANGE

Estimated price range per unit of waste treated :
\$ 25.00 to \$ 75.00 per ton

Vendor Name: TEXAROME, INC.
Technology Type: STEAM STRIPPING

Technology Trade Name: Mobile Solid Waste Desorption

Address: 1.5 Miles East Highway 337
P.O. Box 157
City: Leakey, Texas 78873
USA
Contact: Gueric R. Boucard
Title: President
Phone: (210) 232-6079
Fax: (210) 232-5716
e-mail: Not Provided
Web Page: Not Provided
Status: Pilot scale

ESTIMATED PRICE RANGE

Estimated price range per unit of waste treated :
\$ 200.00 to \$ 1,000.00 per ton

Vendor Name: THERMOTEC SYSTEMS CORPORATION
Technology Type: ROTARY KILN WITH AFTERBURNER

Technology Trade Name: Tandem SRU

Address: 5201 North Orange Blossom Trail
City: Orlando, Florida 32810
USA
Contact: M.A. Howard, P.E.
Title: Product Manager
Phone: (407) 290-6000
Fax: (407) 578-0577
e-mail: Not Provided
Web Page: Not Provided
Status: Full scale

ESTIMATED PRICE RANGE

Estimated price range per unit of waste treated :
\$ 15.00 to \$ 30.00 per ton

Vendor Name: WESTERN RESEARCH INSTITUTE
Technology Type: HOLLOW SCREW

Technology Trade Name: Thermal Treatment Using Screw Reactors

Address: 365 North 9th Street
City: Laramie, Wyoming 82070
USA
Contact: John Nordin/Alan Bland
Title: Senior Research Environmental Engineer
Phone: (307) 721-2443
Fax: (307) 721-2345
e-mail: Not Provided
Web Page: Not Provided
Status: Pilot scale

ESTIMATED PRICE RANGE

Estimated price range per unit of waste treated :

\$ _____ to \$ _____ per _____

Vendor Name: WESTINGHOUSE REMEDIATION SERVICES, INC.
Technology Type: INFRARED FURNACE WITH RECOVERY

Technology Trade Name: Westinghouse Thermal Desorption Unit (TDU)

Address: 675 Park North Boulevard
Building F, Suite 100
City: Clarkston, Georgia 30021-1962
USA
Contact: Jeff Rouleau
Title: Project Engineer
Phone: (404) 299-4698
Fax: (404) 296-9752
e-mail: Not Provided
Web Page: Not Provided
Status: Full scale

ESTIMATED PRICE RANGE

Estimated price range per unit of waste treated :

\$ 150.00 to \$ 300.00 per ton

APPENDIX

C



Appendix C: Contaminant Concentration Equations

C.1 Stack Emission Equations

Equation C-1. Conversion of Particulate Concentration in gr/dscf to mg/m³.

$$X \frac{mg}{m^3} = Y \frac{gr}{dscf} \left(\frac{1\text{lb}}{7000\text{ gr}} \right) \left(\frac{453.6 \times 10^3 \text{ mg}}{1\text{ lb}} \right) \left(\frac{T_1 \text{ dscf}}{T_2 \text{ acf}} \right) \left(\frac{35.3145 \text{ ft}^3}{1 \text{ m}^3} \right)$$

Where: Y = Given concentration

T₁ = Standard temperature (298.15 K)

T₂ = Stack exhaust temperature (505.37 K)

Equation C-2. Conversion of Dioxin and Furan Concentration in ng/dscm to mg/m³.

$$X \frac{mg}{m^3} = Y \frac{ng}{dscm} \left(\frac{1\text{ mg}}{10^6\text{ ng}} \right) \left(\frac{T_1 \text{ dscf}}{T_2 \text{ acf}} \right)$$

Equation C-3. Conversion of HCl Concentration in lbs/hr to ppm.

$$X \text{ ppm} = Y \frac{\text{lbs}}{\text{hr}} \left(\frac{1\text{ hr}}{\dot{m}(\text{air}) \text{ lbs}} \right) \left(10^6 \text{ ppm} \right)$$

Equation C-4. Calculation of \dot{m} for use in Equation C-3.

$$\dot{m}(\text{air}) \frac{\text{lbs}}{\text{hr}} = \dot{m}(\text{air}) \text{ acfm} \left(\frac{60 \text{ min}}{1 \text{ hr}} \right) \left(\frac{0.7\text{ g}}{\text{L}} @ 505.37\text{ K} \right) \left(\frac{1000 \text{ L}}{1 \text{ m}^3} \right) \left(\frac{1 \text{ m}^3}{35.3145 \text{ ft}^3} \right) \left(\frac{1\text{ lb}}{453.6\text{ g}} \right)$$

Equation C-5. Conversion of SO₂ Concentration in g/sec to mg/m³.

$$X \frac{mg}{m^3} = Y \frac{g}{\text{sec}} \left(\frac{1000\text{mg}}{1\text{g}} \right) \left(\frac{1\text{min}}{8200\text{ft}^3} \right) \left(\frac{60\text{sec}}{1\text{min}} \right) \left(\frac{35.3145 \text{ ft}^3}{1 \text{ m}^3} \right)$$

Where: 8200 acfm is the stack gas flow rate at Pristine, Inc.

Equation C-6. Conversion of PCB and PEG Concentration in lbs/hr to mg/m³.

$$X \frac{mg}{m^3} = Y \frac{lbs}{hr} \left(\frac{1 \text{ min}}{5275 \text{ ft}^3} \right) \left(\frac{298.15 \text{ dscm}}{505.37 \text{ acm}} \right) \left(\frac{1 \text{ hr}}{60 \text{ min}} \right) \left(\frac{453.6 \times 10^3 \text{ mg}}{1 \text{ lb}} \right) \left(\frac{35.3145 \text{ ft}^3}{1 \text{ m}^3} \right)$$

Where: 5275 scfm is the stack gas flow rate at Wide Beach.

Equation C-7. Conversion of Toxaphene and DDT Concentrations in µg/m³ to mg/m³.

$$X \frac{mg}{m^3} = Y \frac{\mu g}{m^3} \left(\frac{1 \text{ mg}}{10^6 \mu \text{g}} \right)$$

C.2 Fugitive Dust Equations (USEPA, 1992)

The following equations are used to estimate the ambient contaminant concentration at various distances from the emission source during excavation. The results of Equations C-8 and C-9 are multiplied by the dispersion factor found in Figure C-1 to estimate the ambient concentration.

Equation C-8. Calculation of Long-Term Emission Rate.

$$ER_{LT} = \frac{(S_v)(C)(\beta)}{t_R}$$

Where:

ER_{LT} = Long-term emission rate (g/sec)
S_v = Volume of soil to be excavated (m³)
C = Average contaminant concentration (µg/g)
β = Bulk density of soil (g/cm³)
t_R = Duration of remediation (sec)

Equation C-9. Calculation of Short-Term Emission Rate.

$$ER_{ST} = ER_{ps} + ER_{diff}$$

Where: ER_{ST} = Short-term emission rate (g/sec)
 ER_{ps} = Emission rate from pore space (g/sec)
 ER_{diff} = Emission rate from diffusion (g/sec)

Equation C-10. Calculation of Emission Rate from Pore Space.

$$ER_{ps} = (0.91)(P)(Q)$$

Where: P = Vapor pressure of contaminant (mm Hg)
 Q = Excavation rate (m^3/sec)

Equation C-11. Calculation of Emission Rate Due to Diffusion.

$$ER_{diff} = \frac{(C)(10,000)(SA)}{\left(1.22 \times 10^6\right) \frac{C}{P} + \left(1.79 \times 10^9 \frac{C}{P}\right)^{\frac{1}{2}}}$$

Where: SA = Emitting surface area (m^2)

Figure C-1. One-Hour Average Downwind Dispersion Factor vs. Distance for Excavation with No Air Controls.

